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A Final Report of Phase I

on

"<u>OVERPRESSURED MARINE SEDIMENTS</u>"

A Research Project for the U.S. Geological

Survey - Conservation Branch - Metairie, La.

by

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Project Number 3249

January 1977

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SYMBOLS

A = net attractive force between grains (cohesion)

A_m = area of mineral

A_t = total area of water and mineral

A_w = area of water

C_{vs} = specific heat of the soil

C_{vw} = specific heat of the water

$\mathring{E}_s$ = rate of change of internal energy of soil

$\mathring{E}_w$ = rate of change of internal energy of water

F_s = force in the soil

F_w = force in the water

f_d = drag force between water and soil

G_s = specific gravity of solids

G_w = specific gravity of water

g = gravitational constant

H = mercury height (back pressure)

h_{el} = elevation head

h_{ex} = excess pore pressure head

h_{hy} = hydrostatic head

h_s = heat flux through the soil alone

h_{sw} = heat flux from soil to water

h_w = heat flux in the water alone

h_{ws} = heat flux from water to soil

i = hydraulic gradient

K = coefficient of earth pressure

K_o = coefficient of earth stress at rest

k = coefficient of permeability

L = length of soil sample

n = porosity

P = head water pressure

S = the slope of the Fermi function at the point of reflection

T/S= the distance from the point of reflection to Y axis in the rectangular co-ordinate system

u = pore pressure in the water (all tensile stresses are considered positive)

V_s = volume of the soil

V_t = total volume

V_v = volume of the voids

V_w = volume of water

V_a = approach velocity based on the total area of mineral and rock

V_s = velocity of settlement downward

V_w = velocity of water flow upward

W_s = weight of the soil

z = space dimension which is positive upward

B, C, D, F, G, J, M, Q, and R are arbitrary constants in various equations.

α_s = coefficient of heat conductivity of the soil

α_w = coefficient of heat conductivity of the water

γ_{by}= buoyant weight of soil = $\gamma_t - \gamma_w$

γ_t = total unit weight of soil and water

γ_w = unit weight of water, assumed to be constant

$\dot{\varepsilon}_v$ = rate of strain in vertical direction

θ_s = temperature of the soil

θ_w = temperature of the water

σ = total stress acting on the total area

$\bar{\sigma}$ = effective stress

$\bar{\bar{\sigma}}$ = intergranular stress

σ_{mf} = mean principal stress at shear failure

σ_{mo} = mean principal stress when there are no shear stresses

σ_v = vertical stress

τ_{octf} = octahedral shear stress at failure

ABSTRACT

The squeezing and ejecting of entrapped overpressured water from clay into sand aquifers is advanced as an explanation for the source of energy for blowouts during well drilling, artesian flow of wells, and the land subsidence where pumping has occurred. During clay sediment deposition and progressive burial entrapped water can be overpressured if the permeability decreases faster than the porosity. Laboratory tests presented for clays show that the permeability decreases from 6 to 12 orders of magnitude faster than porosity. Misapplication of Terzaghi's effective stress principal leads to the conclusion that the water stress cannot exceed the overburden stress, but the conclusion should have been that the water force cannot exceed the overburden force. If the water area is small and the water force supports a significant part of the overburden froce then the pore pressure can be much higher than the overburden stress.

Since the water stress at the interface between clay and sand must be equal, ultra high hydraulic gradients can develop to force the water from clay to the sand allowing the clay to consolidate and the water in the sand to overpressure.

All available Thermo-Mechanical field equations are presented for application for a new consolidation theory that does not assume the permeability is a constant and the void ratio is a linear function of effective stress. Laboratory results are presented to show that this is true.

A polynomial equation of state for sea water in terms of pressure and temperature is presented. Through the solution of a non-linear differential equation, the geostatic relationship between depth and water pressure has been determined for a linear increase in temperature with depth. Pressures in excess of this pressure constitutes an "overpressure".

INTRODUCTION

In an overpressured zone in the earth the pore pressure is greater than hydrostatic pressure. Data from over 4,000 wells in the Gulf Coast area show that pore pressures in oil wells are usually between hydrostatic and overburden or geostatic pressures, but in the overpressured region of the Gulf Coast area, some measured pore water pressures even exceed geostatic pressure and are thought to be the major cause of blowouts and stuck drill stems (92). When the logs of over 4000 oil wells were reviewed by Dave Powley of Amoco Oil Company it was found that there were general trends in pore pressure, temperature, resistivity, porosity and sonic velocity as a function of depth. Figure 1 shows these general trends.

During the last 20 years there have been 33 blowouts involving mobile offshore drilling rigs. These failures were distributed all over the world but primarily in areas where the rate of deposition is high (84). Some pertinent data on these accidents are given in Table 1. In the same period there have been 53 blowout accidents involving permanent structures in federal oil and gas operations in the outer continental shelf of the Gulf of Mexico alone (113). Table 2 gives some of the pertinent data on these accidents. If the hazards of overpressured sediments are to be avoided, better techniques must be developed to locate them. These new techniques will depend on the knowledge of how these zones can develop.

In a blowout large amounts of fluid are ejected with great velocity. The kinetic energy may even be sufficient to blow the drill stem out of the bore hole and sometimes blow down the drilling rig itself. Sometimes cavities are created around the bore hole big enough for the rig to fall

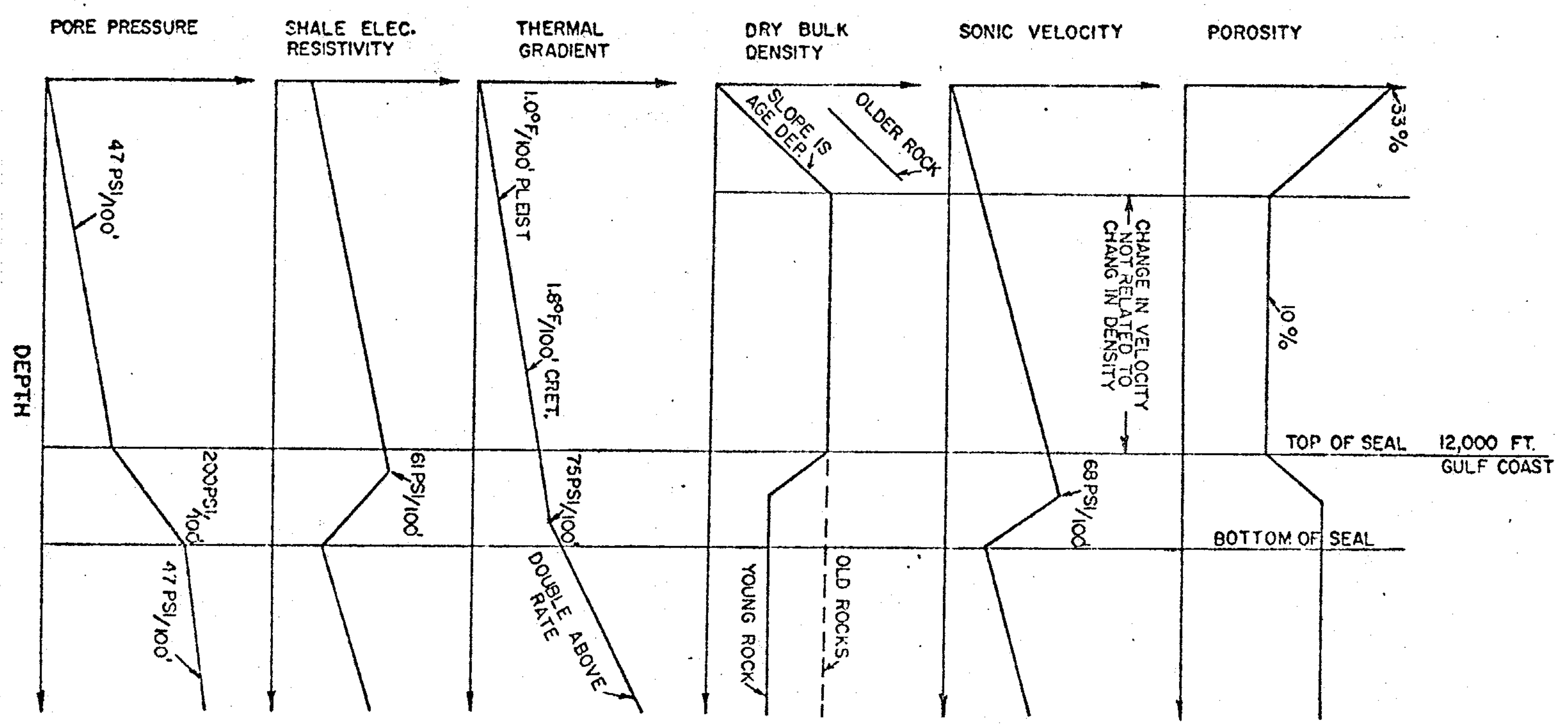


FIG. 1

GENERALIZED RELATIONS BETWEEN DEPTH AND VARIOUS PROPERTIES FOR OVER PRESSURED REGIONS

"AS PRESENTED BY DAVE POWLEY" MAY 15, 1975

Table 1

MOBILE RIG ACCIDENTS ON DRILLING SITE

As taken from Offshore News, June 5, 1974 and Offshore Rig Data Service

YEAR OF ACCIDENT & RIG NAME	OWNER	TYPE	ACCIDENT LOCATION	DESCRIPTION OF ACCIDENT
1975 (11 Accidents total**) *Topper III (300')	Zapata Offshore Houston, Tx.	Jackup	Gulf of Mexico	Leg damage while jacking up. Repaired. Then blowout. Rig not salvaged.
Mariner 2 (600')	Santa Fe	Semi	Gulf of Mexico	Blowout. Repaired.
Discoverer I (600')	Offshore Co.	Ship	Nigeria	Blowout. Repaired.
Times Aver II (100')	Underwater Gas	Jackup	Great Lakes	Repaired.
*Santa Fe Explorer	Santa Fe Orange County, Cal.	Jackup	S.E. Asia	Leg cracking due to fatique.
1974 (21 accident total) *Gatto Selvatico (140')	Saipem Milan, Italy	Jackup	Madaqascar	Leg penetrated crust.
Meteorite Rig 58 (100')	Offshore Co.	Jackup	Nigeria	Blowout.
Penrod 60 (340')	Penrod Drlg.	Jackup	Gulf of Mexico	Damaged in hurricane. Repaired.

* Foundation failure probably involved in accident.

** For each year the total number of accidents includes those that occurred while towing, while the ones listed occurred after the rig was set up.

Table I (continued)

YEAR OF ACCIDENT & RIG NAME	OWNER	TYPE	ACCIDENT LOCATION	DESCRIPTION OF ACCIDENT
*Mr. Louie (120')	Reading & Bates Tulsa	Jackup	Nigeria	Leg failure.
*Gemini (230')	The Offshore Co. Houston	Jackup	Gulf of Suez	Leg collapsed, total loss. Foundation failure.
*George F. Ferris (200')	Raymond Int'l. New York	Jackup	Gulf of Alaska	Jacking System failed. Salvaged.
Havdrill (1500')	Nordic Offshore	Ship	Labrador & Morocco	Lost BOP stack off both Labrador & Morocco. Repaired both.
1973 (4 accidents total) Mariner I	Santa Fe	Semi	Trinidad I	Blowout. Repaired.
*Rowan Anchorage	Rowan Drilling Co. Houston	Jackup	Macassar Strait off E. Kalimantan	Leg collapsed. Salvaged.
1972 (7 accidents total) M.G. Halme	Reading & Bates	Jackup	Java Sea	Blowout (no fire) capsized. Not salvaged.
Rig 60	Transworld Drilling	Jackup	Gulf of Martaban off Burma	Blowout. Lost at Sea. Not salvaged.
J. Storm II	Marine Drilling Company	Jackup	Gulf of Mexico	Blowout. Not salvaged.
*Intrepid	Zapata Off-shore Houston	Jackup	Eugene Island Gulf of Mexico	Leg failure. Salvaged.

Table I (continued)

YEAR OF ACCIDENT & RIG NAME	OWNER	TYPE	ACCIDENT LOCATION	DESCRIPTION OF ACCIDENT
*Mr. Arthur	Fluor Drilling Ser. New Orleans	Submersible	Gulf of Mexico (S. Pass, Block 26)	Major damage. Salvaged.
1971 (5 accidents total) Big John	Atwood Oceanics	Drill barge	Brunei	Blowout. Severe fire. Repaired and returned to service.
Ocean Driller	ODECO	Semi	Louisiana	Gas blowout.
Woodeco II	Fluor	Barge	Peru	Blowout & fire. Not salvaged.
Panintoil II	AMOCO - IRAN (IPAC)	Jackup	Persian Gulf	Damaged by storm. Salvaged.
1970 (16 accidents total) Unknown	Kelly Drilling Co.	Inland Barge		Blowout not salvaged.
*Rig 59	Offshore Co. Houston	Jackup	Nigeria	Leg damage, repaired.
Discoverer III	Offshore Co.	Self-propelled		Blowout damage (no fire). Repaired.
Discoverer II	Offshore Co.	Self-propelled	Malaysia	Blowout, repaired.
E.W. Thornton	Reading & Bates	Catamaran	Malaysia	Blowout, no reported damage.
Stormdrill III	Strom Drilling Co.	Jackup	Texas	Severe fire. Repaired and returned to service.
Mercury	Offshore Co.	Jackup		Heavy weather damage. Salvaged.

Table I (continued)

YEAR OF ACCIDENT & RIG NAME	OWNER	TYPE	ACCIDENT LOCATION	DESCRIPTION OF ACCIDENT
1969 (17 accidents total) Wodeco III	Fluor Drilling Services	Drill barge	Red Sea	Blowout.
John C. Marthens	Offshore Co. Constructors	Jackup	Gulf of Alaska	Leg damage during storm. Repaired.
Rimtide	Rimrock Tidelands ODECO	Submersible	Gulf of Mexico	Blowout, salvaged.
Sedco 135G	SEDCO, Inc.	Semi	Timor Sea	Severe fire damage from blowout. Repaired and returned to service.
1968 (9 accidents total) *Dresser II (Converted to Dresser VII)	Dresser Offshore Houston	Jackup		Capsized. Salvaged.
Little Bob	Coral Drilling Co.	Jackup	Gulf of Mexico	Blowout and fire. Not salvaged.
*Ocean Prince	ODECO New Orleans	Semi	North Sea	Destroyed by storm. Not salvaged.
1967 (zero accidents) NONE				
1966 (4 accidents total) *Sea Gem	Compagnie Gen D'Equipments Paris, France	Jackup	North Sea	Collapsed. Not salvaged.
*Rig No. 52	Offshore Co. Houston	Jackup		Leg damaged. Salvaged.

Table I (continued)

YEAR OF ACCIDENT & RIG NAME	OWNER	TYPE	ACCIDENT LOCATION	DESCRIPTION OF ACCIDENT
1965 (7 accidents total) Triton	Royal Dutch/Shell	Jackup	Nigeria	Blowout & fire.
Paguro	Saipem S.P.A.	Jackup	Adriatic Sea	Blowout & fire.
1964 (2 accidents total) C.P. Baker	Reading & Bates	Drill barge	Gulf of Mexico	Turned end-over-end during blowout and fire. Salvaged.
1963 (Zero accidents) NONE				
1962 (one accident total) NONE				
1961 (3 accidents total) Mr. Louie	Reading & Bates	Jackup	Gulf of Mexico	Damaged in storm, salvaged.
1960 (1 accident total) NONE				
1959 (2 accidents total) *Rig No. 10	Trans-Gulf Morgan City	Jackup	Gulf of Mexico	Capsized. Not salvaged.
C.E. Thornton	Reading & Bates	Jackup	Persian Gulf	Blowout. Extensive fire damage. Repaired.
1958 (2 accidents total) NONE				
1957 (4 accidents total) *Qatar Rig No. 1	Royal Dutch/Shell Holland	Jackup	Persian Gulf	Broken up by sudden storm. Not salvaged.

Table I (continued)

YEAR OF ACCIDENT & RIG NAME	OWNER	TYPE	ACCIDENT LOCATION	DESCRIPTION OF ACCIDENT
*Mr. Gus 1	Glasscock Drilling Company Lafayette La.	Jackup	Gulf of Mexico	Capsized. Lower hull salvaged.
*Deepwater No. 2	Deepwater Drilling Company	Jackup	Gulf of Mexico	Collapsed while drilling. Not salvaged.
1956 (1 accident total) NONE				
1955 (3 accidents total) S-44	Chevron	Submersible	Gulf of Mexico	Blowout & fire. Repaired.
*Rig No. 52	Offshore Co. Houston	Jackup		Jacking-up. Salvaged.

TABLE 2

ACCIDENTS CONNECTED WITH FEDERAL OIL AND GAS OPERATIONS IN THE OUTER CONTINENTAL SHELF GULF OF MEXICO

Blowouts

	Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatal-ities, damage to property or environment
1.	Vermilion Blk. 26 OCS 029, Well A-1 Union Oil Co. of Calif.	6-8-56 to 11-20-56	Blowout, Gas; 11,435' Fire. B/E/	Drilled relief well.	None	Lost platform, rig, and two wells.
2.	Eugene Island Blk. 175 OCS 0438, Well A-6 Sinclair Oil & Gas Co.	10-19-57 (11 hrs.)	Blowout, Gas; 11,290' Fire. B/	Bridged	None	Minor damage to rig.
3.	South Pass Blk. 27 OCS 0353, Well 25 Shell Oil Co.	6-14-58 (2 hrs.)	Blowout, Gas; 1,869' Fire. B/	Bridged	None	Minor damage to rig.
4.	So. Timbalier Blk. 134 OCS 0461, Well D-1 Gulf Oil Corp.	7-26-59 (4 hrs.)	Blowout, Gas; 4,880' Fire. B/E/	Bridged	None	One killed, seven injured, rig damaged.

B/ See also, Explosions and Fires Table B
D/ See also, Significant Pollution Incidents, Table D
E/ See also, Major Accidents Table E

	Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatalities, damage to property or environment
5.	Eugene Island Blk. 199 OCS 0437, Well No. 2 Placid Oil Co.	7-13-60 to 7-27-60	Ship collided with platform causing blowout; gas; fire. B/E/	With blowout preventers.	None	Platform destroyed. Well casing damaged.
6.	Vermilion Blk. 115 OCS 0770, Well 1, Phillips Petroleum Co.	11-18-60 (4 hrs.)	Blowout, Gas; 13,001'.	Bridged	None	None reported.
		11-22-60 (blowout again)		Cemented	None	None reported.
7.	Grand Isle Blk. 9 OCS 035-A, Well 1-34-B Freeport Sulphur Co.	3-18-62 (36 hrs.)	Blowout, Gas; (shallow) fire. B/E/	Ceased	None	Lost rig and relay station on platform.
8.	Eugene Island Blk. 206 OCS 0806, Well No. 1 Texaco Inc.	11-12-63 to 1-22-64	Blowout, Gas; 11,000'. Rig sheared conductor and drill pipe during storm.	Drilled relief well.	None	Minimal damage.
9.	West Delta Blk. 28 OCS 0384, Well 3 Chevron Oil Co.	1-15-64 (12 hrs.)	Blowout, Gas; 10,871'.	Mud	None	None reported.
10.	West Delta Blk. 117 OCS-G 1101, Well A-5 Gulf Oil Corp.	1-20-64 to 1-27-64	Blowout, Gas and oil; fire. B/D/E/	Bridged	100	Platform damaged extensively. No recorded environmental damage.

	Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatalities, damage to property or environment
11.	Eugene Island Blk. 273 OCS-G 0987, Well No. 4 Pan American Petroleum Corp.	6-30-64 to 7-2-64	Blowout, explosion, and fire; gas; 684'. B/E/	Ceased	None	22 fatalities, drilling vessel sank.
12.	Eugene Island Blk. 208 OCS 0576 & 0577 Platforms "A" "C", "D" Continental Oil Co.	10-3-64 (several days)	Blowout, gas and oil; caused by hurricane. Destroyed platform. D/E/	Cemented	5180	Lost platforms. No recorded environmental damage.
13.	Ship Shoal Blk. 149 OCS 0434 Platform "B" Signal Oil Co.	10-3-64 to 10-19-64	Blowout, gas, caused by hurricane. Destroyed platform. E/	Cemented	None	Lost platform.
14.	Eugene Island Blk. 128-A OCS 0442 Well No. 2 Shell Oil Co.	10-4-64 to 10-15-64	Blowout, gas, caused by hurricane. Destroyed platform. E/	Killed with mud.	None	Lost single well support structure.
15.	Ship Shoal Blk. 154 OCS 0420 Platform "D" Gulf Oil Corp.	10-4-64 to 10-19-64	Blowout, gas caused by hurricane damaging platform and well. E/	Bridged	None	Severely damaged platform.

	Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatalities, damage to property or environment
16.	Eugene Island Blk. 158 OCS-G 1220, Well B-3 Shell Oil Co.	3-15-65 to 3-20-65	Blowout, Gas; 15,867'.	Bridged	None	None reported.
17.	Ship Shoal Blk. 29 OCS 0345, Well No. 7 AMOCO	7-19-65 to 7-26-65	Blowout, Gas & condensate; 17,086'. D/E/	Killed well with mud.	1,688	Minimal
18.	West Delta Blk. 117 OCS-G 1101 Platform "A" Gulf Oil Co.	9-10-65 (Several days)	Blowout, oil, caused by hurricane. Destroyed platform. E/	Cemented	Minimal	Lost platform.
19.	So. Marsh Island Blk. 48 OCS 0786, Well B-4 Gulf Oil Co.	9-16-65 to 4-22-66	Blowout, gas; 800'.	Cemented	None	None reported.
20.	So. Timbalier Blk. 21 OCS 0263, Well No. 70 Gulf Oil Co.	9-25-65 to 10-8-65	Blowout, gas; 11,716'. E/	Ceased	None	Removed rig before well cratered (lost well).
21.	Ship Shoal Blk. 208 OCS-G 1294 Union Oil Co. of Calif.	2-5-66 (15 min.)	Blowout, oil; (workover).	Installed valve.	Minimal	None reported.

	Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatalities, damage to property or environment
22.	Eugene Island Blk. 275 OCS-G 0988, Well A-9 Texaco, Inc.	2-13-66 to 2-15-66	Blowout, oil & gas; 10,561'.	Ceased	Minimal	Little damage.
23.	So. Timbalier Blk. 67 OCS 020, Well C-12 Humble Oil & Refining Co.	4-17-67 (8 hrs.)	Blowout, gas; 1,477'.	Bridged	None	One corner platform settled.
24.	Ship Shoal Blk. 214 OCS 0828, Well No. 2 Kerr-McGee Corp.	10-30-67-- Collision 9-8-68 to 9-29-68	Blowout, gas & Condensate. Freighter collided w/well (Blowout occurred 1 year after collision). E/	Cut casing and cemented.	Minimal	Lost well and caisson protection.
25.	South Pass Blk. 62 OCS-G 1294 Shell Oil Co.	6-?-68	Blowout, gas; 8,426'.	Cemented through drill pipe.	None	Lost drill pipe.
26.	Grand Isle Blk. 43 OCS 0175 Continental Oil Co.	9-?-68 (several days)	Blowout, gas; 14,184'.	Bridged	None	None reported.
27.	So. Timbalier Blk. 67 OCS 020 Well C-16 Humble Oil & Refining Co.	9-28-68 (9 hrs.)	Blowout, gas; 910' Fire. (While running 16".) B/E/	Bridged	None	Platform rig damaged and removed, platform settled.

	Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatalities, damage to property or environment
28.	So. Marsh Island Blk. 38 OCS 0784 Pan American Petroleum Corp.	10-30-68 (1 day)	Blowout, gas; 387'.	Bridged	None	None reported.
29.	Vermilion Blk. 119 OCS 0487, Well D-11 Continental Oil Co.	11-24-68 (12 hrs.)	Blowout, gas; 9,544'.	Bridged	None	None reported.
30.	Vermilion Blk. 46 OCS 079, Well A-3 Mobil Oil Corp.	3-14-69 to 5-16-69	Blowout, gas & condensate; 3,600'. E/	Mud--Drilled relief well.	Minimal	Had to plug well. Platform settled.
31.	Ship Shoal Blk. 72 OCS 060, Well No. 3 Mobil Oil Corp.	3-16-69 to 3-19-69	Blowout, oil; 9,034' rig shifted & sheared well head. D/E/	Capped	2,500	No recorded environmental damage.
32.	So. Timbalier Blk. 26 OCS-G 1870, Platform "B" Shell Oil Co.	12-1-70 to 4-17-71	Blowout, gas, explosion; during wire-line work on well. B/D/E/	Ten relief wells drilled.	53,000	Four killed, 27 injured, lost platform. Minor amounts of oil on beaches.
33.	Ship Shoal Blk. 293 OCS-G 1043, Well B-10 Shell Oil Co.	12-19-70 (4 hrs.)	Blowout, oil; while drilling.	Bridged	Minimal	None reported.

	Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatalities, damage to property or environment
34.	West Cameron Blk. 639 OCS-G 2027, Well No. 1 Sun Oil Co.	3-3-71 to 3-6-71	Blowout, gas; 3,956'. E/	Bridged	None	BOP assembly and drill pipe lost. Lost well.
35.	West Cameron Blk. 180 OCS 0763, Well A-4 (and A-4D, A-4T) Tenneco Oil Co.	6-4-71 to 6-5-71	Blowout, gas; sub-sea leak.	Platform was shut-in. Well killed with mud.	None	None reported.
36.	Vermilion Blk. 147 OCS 2071, Well No. 1 Union Oil Co.	6-30-71 (2 hrs.)	Blowout, gas; 12,910'.	Bridged	None	Minimal
37.	South Pass Blk. 28 OCS 0694, Well No. 64 Shell Oil Co.	7-16-71 to 7-18-71	Blowout, gas; workover, 8,106', casing valve failure.	Mud	None	Minimal equipment damage.
38.	Eugene Island Blk. 215 OCS 0578 Platform "B" Wells Nos. B-1, B-2, B-3, B-4, & B-5 AMOCO	10-16-71 to 12-10-71	Explosion and fire at oil pump. Cause unknown. B/D/E/	Drilled 4 relief wells and shut-in safety valves.	450	Lost production platform and equipment. No recorded environmental damage.
39.	West Cameron Blk. 28 OCS-G 2125 Well No. 3 Chevron Oil Co.	10-27-72 (2-1/2)	Blowout, gas; 15,597'.	Bridged	None	Minimal damage.

	Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatalities, damage to property or environment
40.	South Pass Blk. 78 OCS-G 2185 Well No. 2 Pennzoil Company	12-3-72 to 12-5-72	Blowout, gas; 3850' with last string of casing set at 1,018' . B/E	Bridged	Minimal	Mobil rig collasped and was lost in crater where well blew out and burned.
41.	Ship Shoal Blk. 269 OCS-G 1036 Well B-3 Union Oil Company of California	12-14-72 (6 hours)	Blowout with dry gas routed through diverter line.	Bridged	None	Minimal damage.
42.	South Marsh Island Blk. 268, OCS-G 2310 Well No. 2 Placid Oil Company	5-5-73 to 5-26-73	Underground blowout while drilling, gas; 11,393' . E/	Bridged	None	Lost well.
43.	West Cameron Blk. 543, OCS-G 2010 Platform A Well A-4 Kerr-McGee Corp.	10-1-73 to 10-2-73	Blowout, explosion, and fire; gas; 8,540' .B/E	Bridged	Minimal	All equipment on the platform was destroyed or heavily damaged. Three men received minor injuries.
44.	South Marsh Island Block 184 OCS-G 2295 Well No. 1 Sun Oil Company	12-11-73	Blowout, gas; 1,210'.	Conductor pipe cemented; mud weight increased.	None	Minimal damage.

Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatalities, damage to property or environment
45. East Cameron Block 338 OCS-G 2063 Platform "A" Well A-6 Sun Oil Co.	6-10-74 (5 hours)	Blowout, gas; TVD 2900'.	Bridged	None	Minimal damage.
46. South Pelto Block 20 OCS 073 Platform "13" Well No. 13 ODECO	9-7-74	Casing valve broken off the wellhead by hurricane. D/	Well was killed with calcium chloride.	75	No recorded environmental damage.
47. South Timbalier Block 26 OCS-G 1870 #7 Kill Well Shell Oil Co.	9-20-74	Hurricane bent casing. Two weeks later casing broke and gas blowout occurred.	Bridged.	None	Damage to casing. Well now P&A.
48. Grand Isle Block 9 OCS 035-S Well No. 27 Freeport Sulphur Co.	12-16-74 (21 hours)	Uncontrolled flow of mine bleed water; TVD 2581'.	Installed full opening block valve.	None	None
49. South Pelto Block 19 OCS 073 Platform "12" Well No. 12 ODECO	12-22-74 to 12-31-74	Casing and tubing sheared at the mudline while attemping to repair hurricane damage. D/	Well re-entered and flow directed into storage tanks.	200	No recorded environmental damage. Well now P&A.

	Area and Block Lease & Well No. Operator	Date and Duration	Type Accident, Related Depth	How Controlled	Volume Oil Spilled (bbls.)	Injuries, fatalities, damage to property or environment
50.	West Cameron Block 289 OCS 0752 Well No. 1 Mobil Oil Corp.	3-18-75	Underground gas seepage around drive pipe during workover.	Plugged and abandoned well.	None	Lost well.
51.	High Island Block A-471 OCS-G 2690 Well No. 1 Mobil Oil Corp.	3-19-75	Blowout, gas; 1,150'. E/	Bridged	None	Lost well and rig.
52.	High Island Block A-595 OCS-G 2721 Well No. 1 Mobil Oil Corp.	4-22-75	Blowout, gas; 2545'.	Bridged	None	Lost well.
53.	South Marsh Island Block 50 OCS 0788 Platform "B" Amoco	6-12-75	Well blew out during completion operations. Escaping gas caught fire and burned for two days. Gas still blowing on June 30. B/ E/	Unknown	Unknown	Platform Drilling Deck and Equipment Damaged by Fire.

into. If gas is present in the fluid it may catch afire and the rig may burn. Blowouts occur throughout the world and are not confined to offshore localities and to deep oil wells. In fact, blowouts have occurred of depths as little as 185 ft. (92).

Overpressured sediments have been the subject of much speculation and several theories have been advanced to explain them. It is usually tacitly assumed that given enough time all pore pressures must decrease to a steady state hydrostatic condition, therefore most explanations involve some method of generation of either pressure or additional water.

One group of papers describes the possibility of sediment settling with no decrease in porosity or no expulsion of water (3,47,74). Since the water will be heated because of the earth's thermal gradient, pressure will be developed. This process requires an impermeable barrier and some hiatus in the consolidation process.

Another group of papers describes the generation of water by chemical alteration of the minerals (22,50,62,91). According to Powley (92), the cores from many overpressured oil wells are nearly identical mineralogically to the sediments being deposited. This raises doubts as to the reliability of the chemical alternation theory. Certainly this theory cannot explain near surface overpressured sediments.

The mechanical process of sedimentation has generally been overlooked as a source of overpressures, and in fact, it has been thought that it is impossible for pore pressures ever to exceed the geostatic pressure. The reason for this belief is Terzaghi's effective stress principal which states the total stress is equal to the sum of the effective stress in the soil and the pore pressure in the water. It is reasoned that the maximum pore pressure would be equal to the maximum total stress or the geostatic stress when the effective stress is zero. This assumption is debatable, since the area of the mineral and the area of the water are also involved.

For equilibrium at any depth and time the force in soil plus the force in the water must equal the total weight of the overburden. Since force is a stress times an area, the stress in soil times the area of the soil fabric is the soil force and the pore water pressure times the area not occupied by the soil fabric is the water force. The area of the water at any depth is equal numerically to the porosity and the area of the soil fabric at the same depth is one minus the porosity.

With progressive burial, additional deposition or a change in the water level the water forces and soil forces must change. Any change in the soil fabric force causes a change in the porosity and any change in porosity causes a change in permeability. If in this process (as in a clay) the permeability decreases faster than the porosity the water will be entrapped. Further loading will only cause the pressure in the water to increase. Conceivably this pressure could increase to the point that the pressure in the water times the area of the water was equal to the overburden load. Since the area of the water is the porosity the maximum pore pressure that could develop would be the overburden divided by the porosity. If the porosity was 10% then the pore pressure might approach 10 times the overburden pressure.

However, blowouts occur only when there is available source of water with a high internal energy that can be readily converted into kinetic energy. The only geologic structure that can satisfy both requirements is a very porous sand or gravel material with high permeability in which the fluids are under high pressure.

Since the sand or gravel structures (aquifers) are so stiff and permeable it is almost impossible for the pore pressures in excess of hydrostatic to develop unless they are confined by soft and almost impermeable clays. Once confined the pore fluid can be overpressured by heat or by pumping additional fluid into the pore space.

The pore pressure at the interface of a clay layer and a sand layer must be equal. If there is a high pore pressure in the clay and low pore pressure in the sand an ultra high hydraulic gradient will be established and water will flow slowly into the sand and overpressure the water in the sand.

Thus the source of water for a blowout is the water in the sand layer. The source of energy is the weight of the overburden causing the overpressures in the clay which induces the overpressures in the sand.

Just as with blowouts, ground subsidence that develops from ground water removal is controlled by the permeability of the clay layer adjacent to a sand layer or aquifer. In fact a flowing or artesian well is nothing more than a controlled blowout. Subsidence develops when there has been sufficient flow so that the pore pressure in aquifer is lowered causing a new flow of water from the overpressure clay. As the water flows out of the clay, the clay consolidates and the surface subsides. The blowout is the initial effect of piercing the aquifer, the artesian flow the second effect as the elastically compressed water expands and the final effect is the subsidence which may continue for many years after pumping is stopped.

All of these phenomena are controlled by the properties of the clay as it develops the high excess pore pressures. The study of clay is complicated by the fact that the clay particles are roughly the same size as water molecules. The pore pressure in clay has never been measured; what has been measured and called the clay pore pressure is the pressure in the water adjacent to the clay.

The detection of potential blowout sites depends on the detection of clays or shales for which the permeability decreases faster than the porosity when loaded.

This work has two purposes. The first is to develop a theory to explain the non-chemical development of excess pore pressures. The research has made use of all of the thermo-mechanical field equations and has led to the reexamination of assumptions or dogma that through repeated use has developed the flavor of truth.

The second purpose of the study is to develop test equipment and procedures to determine empirically for fine grained marine sediments the relationships between: 1) the consolidation pressure and porosity, and 2) the permeability and porosity, so that the effects of the mechanical process could be reevaluated to determine if progressive burial of sediment automatically causes overpressures to develop.

The theoretical study is partially complete and the progress is given in the following pages. The experimental equipment has been developed and exciting results have been obtained. This report summarizes the result of Phase I or the first years work on "Overpressured Marine Sediments." The total work is envisioned as a four year study.

This work needs to be extended to include the effect of heating as the soil is progressively buried. Other clays with different mineralogical make up need to be tested to verify the general theory being developed.

This work will have application in areas other than the study of blowouts and the artesian withdrawal of water from a aquifier. Some of these areas are:

1. Settlement rates of river deltas and ocean basins;
2. Subsidence rate of onshore areas due to production of oil and water wells,
3. Instability of submarine sediments that cannot drain and develop shear strength as it affects submarine slopes, stationary platforms, mobile platforms that bear on the bottom and pipelines laid on the ocean bottom;
4. Local effects that contribute to diapirism, folding and faulting and;
5. Sediment layering which causes reflections and refraction of sound waves in exploration.

THEORETICAL STUDY

The theoretical work has followed four lines of investigations. They are as follows:

I. Reexamination of assumptions generally accepted as truth. These assumptions are for the application of Terzaghi's effective stress, Archimedes buoyancy principle, and the seepage force concept to consolidation problems.

II. Redevelopment of the consolidation equation using the thermo-mechanical field equations without the simplifying assumptions of constant permeability and a linear relationship between void ratio and effective stress which is known to be wrong. "Darcy's law" for flow through porous media was used but this relationship also needs reexamination. The field equations considered are applied to the soil and water individually. They are for the conservation of mass, linear momentum and energy. The "Fourier heat conduction law" and the specific heat concept is also used without reexamination.

III. A nonlinear equation of state for sea water has been developed from literature sources. It gives the density of water as a function of pressure and temperature. The relationship between depth and pressure has been determined for sea water in the soil where the temperature increases linearly with depth. This is the geostatic condition for sea water in soil.

IV. The possibility of shear plane development in the soil as it is progressively buried has also been studied. This could have a major influence on permeability and strength of the sediment.

The progress in each one of these areas is as follows.

I. Reexamination of the Assumptions

A. Reexamination of the Terzaghi's effective stress principle.

These concepts or ideas have been reexamined to see if they really apply to saturated soil or rock and if they do what the restrictions are.

Applying the equivalence concept, the force on any plane in a material must be equal to the force on the other side of the plane. The stresses integrated over areas give forces. Considering the normal stresses in a geostatic situation as shown in Figure (2) it is seen that:

$$\sigma \cdot a_t = (\bar{\bar{\sigma}} + A)\, a_m + u a_w \qquad (1)$$

where

a_t = total area of water and mineral

a_m = area of mineral

a_w = area of water

σ = total stress acting on the total area

$\bar{\bar{\sigma}}$ = intergranular stress

A = net attractive force between grains (cohesion) and

u = pore pressure in the water (All tensile stresses are considered positive)

If the total area $a_t = 1$ and the total volume $V_t = 1$, then the average area of the mineral $a_m = 1\text{-}n$ and the average area of the water $a_w = n$, if the porosity n is the volume of the void V_v divided by the total volume V_t.

Heretofore, it has been contended that the pore pressure u could never exceed the geostatic stress σ because Terzaghi's effective stress principal

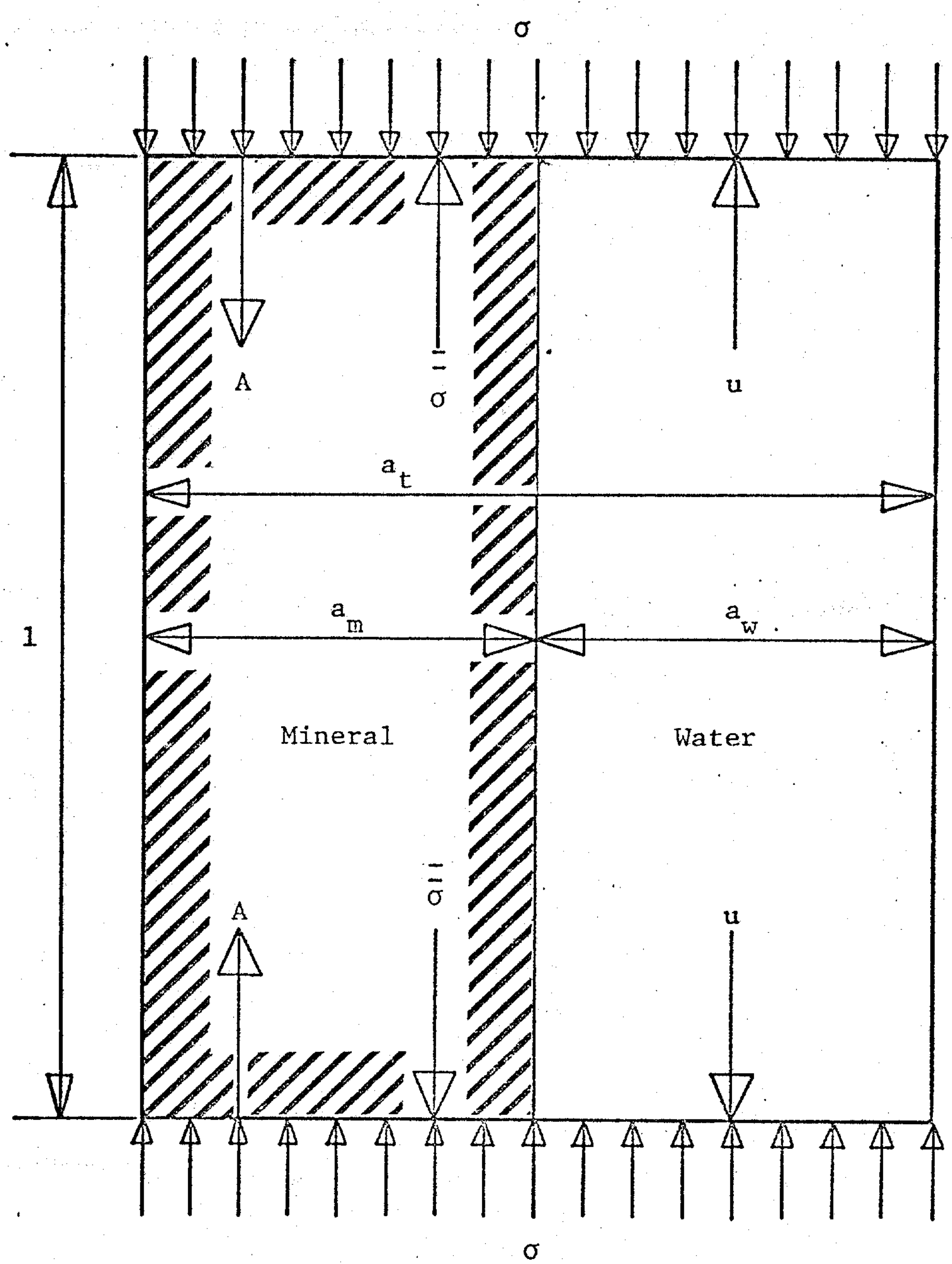


Figure 2
Schematic of water-mineral system

was considered to be fact as given by

$$\sigma = \bar{\sigma} + u \tag{2}$$

This relationship requires that all three stresses act over the total area, $a_t = 1$, which of course, is impossible. $\bar{\sigma}$ is called the effective stress.

Solving for the pore pressure u is seen that:

$$u = \frac{\sigma}{n} - \frac{(1-n)(\bar{\bar{\sigma}} + A)}{n} \tag{3}$$

Should the net attractive force between particles a and the intergranular stress $\bar{\bar{\sigma}}$ be zero then

$$u = \frac{\sigma}{n} \tag{4}$$

This implies that if the porosity n is 10% the pore pressure U could theoretically be 10 times as large as the total overburden stress.

B. Archimedes buoyancy principal

To study the Archimedes principal the equation of linear momentum for the static case is written

$$\frac{\partial Fs}{\partial z} + \frac{\partial Fw}{\partial z} = \gamma_t \tag{5}$$

where F_s = force in the soil

F_w = force in the water

γ_t = total unit weight of soil and water

z = space dimension which is positive upward

If the area of the water a_w is equal to the total area $a_t = 1$ then

$$\frac{\partial Fs}{\partial z} + \frac{\partial u}{\partial z} = \gamma_t \qquad (6)$$

This of course implies that the a_m is zero. The pore pressure u is

$$-u = \gamma_w (h_{hy} + h_{ex}) \qquad (7)$$

where

γ_w = unit weight of water, assumed to be constant

h_{hy} = hydrostatic head

h_{ex} = excess pore pressure head

The hydraulic gradient i is defined for a constant density fluid as

$$-i = \frac{\partial h}{\partial z} \qquad (8)$$

where

$$h = h_{el} + h_{hy} + h_{ex} \qquad (9)$$

and

h_{el} = elevation head

Therefore

$$-h = \frac{\partial h_{el}}{\partial z} + \frac{\partial h_{hy}}{\partial z} + \frac{\partial h_{ex}}{\partial z} \qquad (10)$$

and since

$$\frac{\partial h_{el}}{\partial z} = 1 \qquad (11)$$

then

$$i = -1 + \frac{1}{\gamma_w} \frac{\partial u}{\partial z} \qquad (12)$$

or

$$\frac{\partial u}{\partial z} = \gamma_w (1 + i) \tag{13}$$

When this is combined with the static equilibrium equation and the assumption of the water acting over the entire area which is unity, it is seen that

$$\frac{\partial Fs}{\partial z} + (1+i)\ \gamma_w = \gamma_t \tag{14}$$

This equation can be rewritten as

$$\frac{\partial Fs}{\partial z} + i\gamma_w = \gamma_t - \gamma_w = \gamma_{by} \tag{15}$$

It can be called the buoyancy equation if there is no flow and no hydraulic gradient and the equation becomes

$$\frac{\partial Fs}{\partial z} = \gamma_{by} \tag{16}$$

This is the mathematical form of Archimedes principle. It is only applicable when the contact area of the mineral is zero and there is no flow.

C. Seepage force

The buoyancy equation can also be used to define the seepage force

$$\frac{\partial Fs}{\partial z} = \gamma_{by} - i\gamma_w \tag{17}$$

The term on the extreme right gives the seepage force. It is usually thought of as the product of the hydraulic gradient and the unit weight of water. Again it requires that the area of the water be equal to the total area and the velocity of the soil and the water to be constant.

Quicksand is usually thought to develop when the bouyancy equation is set equal to zero and

$$\gamma_{by} = i\gamma_w \tag{18}$$

or

$$i = \frac{\gamma_{by}}{\gamma_w} \sim 1 \tag{19}$$

This can result when

$$\frac{\partial Fs}{\partial z} = 0 \tag{20}$$

and the Fs must only be constant, not zero. It can be seen that the quick condition also requires that the force in the soil F_s be zero. Again the statics must prevail and the area of the water must be equal to the total area. Each of the statements also assumes that the unit of water is a constant.

II. Redevelopment of the Consolidation Equations Using Darcy's Law and Field Equations

A. Conservation of Mass

Although Darcy's law was developed for flow through sand and may not be applicable to flow through clay it states that

$$v_a = ki \tag{21}$$

where v_a = is the approach velocity based on the total area of mineral and rock

k = is the coefficient of permeability and

i = is the hydraulic gradient

For mass to be conserved at any depth the flow of water upward or out of the soil must be equal to the flow of the mineral downward or out of the water.

This would require that

$$v_s = \frac{-ki}{1-n} = \text{velocity of settlement downward} \tag{22}$$

and

$$v_w = \frac{ki}{n} = \text{velocity of water flow upward} \tag{23}$$

When each of these flows are multiplied by their respective areas it is seen that mass is conserved.

These flows can also be related to the change of porosity of the mineral by the following equation.

$$\frac{\partial ki}{\partial z} = \frac{\partial n}{\partial t} \tag{24}$$

This assumes that the water is incompressible.

If this is not assumed, then for the water the following equation must hold

$$\frac{\partial (\gamma_w ki)}{\partial z} = \frac{\partial (n\gamma_w)}{\partial t} \tag{25}$$

and for the soil

$$\frac{\partial (\gamma_s ki)}{\partial z} = \frac{\partial (1-n)\gamma_s}{\partial t} \tag{26}$$

In the first of these equations the unit weight of water is γ_w which is defined as

$$\gamma_w = G_w \gamma_o \tag{27}$$

where G_w is the specific gravity and a function of both temperature Θ and water pressure u and γ_o = unit weight of water at 4^oC and at one atmosphere of pressure. The equation for the specific gravity of sea water has been developed from literature sources and is given later.

Also $\gamma_s = G_s \gamma_o$ (28)

where G_s is the specific gravity of the solids. The specific gravity of the solids G_s varies little in the range of interest since the mineral is one order of magnitude less compressible than the water.

For the soil the continuity equation reduces to

$$\frac{\partial ki}{\partial z} = \frac{\partial n}{\partial t} \quad (29)$$

and using this equation with the similar equation for water it is found that

$$\frac{ki\partial\gamma_w}{\partial z} = \frac{n\partial\gamma_w}{\partial t} \quad (30)$$

B. Equation of motion

The equation of motion can be also written for both the soil and the water separately.

For the soil

$$\frac{\partial(\bar{\bar{\sigma}} + A)}{\partial z}(1-n) - W_s + f_d = \frac{d(\frac{W_s}{g})\, v_s}{dt} \quad (31)$$

where $\bar{\bar{\sigma}} + a$ is the stress in the soil acting over the area of the soil as

W_s is the weight of the soil and equal to the $V_s G_s \gamma_o$

V_s is the volume of the soil and equal to 1-n

f_d is the drag force between water and soil

Substitution of these values yields

$$\frac{\partial(\bar{\bar{\sigma}}+A)\ (1-n)}{\partial\ z} - (1-n)\ G_w\gamma_o + f_d = \frac{-G_s\gamma_o}{g}\ \frac{d(ki)}{dt} \tag{32}$$

A similar equation can be developed for the water. It is

$$\frac{\partial(un)}{\partial\ z} - nG_w\gamma_o - f_d = \frac{G_w\gamma_o}{g}\ \frac{d(ki)}{dt} \tag{33}$$

if it is assumed that the unit weight of water is a constant. These two equations when added become

$$\partial\ \frac{[(\bar{\bar{\sigma}}+A)\ (1-n)+un]}{\partial\ z} - [(1-n)G_s\gamma_o + nG_w\gamma_o] = \frac{\gamma_o}{g}\ [G_w-G_s]\frac{d\ ki}{dt} \tag{34}$$

and this equation can be reduced to

$$\frac{\partial\sigma}{\partial\ z} - \gamma_T = -\gamma_o[G_s - G_w]\ \frac{d(ki)}{dt} \tag{35}$$

where

σ is the total stress

γ_t is the total unit weight

and g is the gravitational constant.

Subtraction of the two equations of motion allows the drag force f_d to be evaluated.

C. Conservation of energy

The energy equation can be written for both the soil and the water. For the soil in uniaxial strain it is

$$\frac{\gamma_s}{g} \overset{\circ}{E}_s = (\bar{\bar{\sigma}}_v + A) \overset{\circ}{\varepsilon}_v + \frac{\partial h_s}{\partial z} + h_{sw} \qquad (36)$$

where

γ_s = $G_s \gamma_o$

$\overset{\circ}{E}_s$ = rate of change of internal energy that includes the potential energy

$\bar{\bar{\sigma}}_v + A$ = intergranular stress in vertical direction

$\overset{\circ}{\varepsilon}_v$ = rate of strain in vertical direction and

$$\frac{\partial v_s}{\partial z} = \frac{\partial\left(\frac{ki}{1-n}\right)}{\partial z} \qquad (37)$$

h_s = heat flux through the soil alone

h_{ws} = heat flux from water to soil

For the water the energy equation can be written

$$\frac{\gamma_w}{g} \cdot \overset{\circ}{E}_w = u\overset{\circ}{\varepsilon}_v + \frac{\partial h_w}{\partial z} + h_{sw} \qquad (38)$$

where

γ_w = $G_w \gamma_o$

$\overset{\circ}{E}_w$ = rate of change of internal energy of the water

u = pore pressure in the water

$$\overset{\circ}{\varepsilon}_v = \frac{\partial V_w}{\partial z} = \frac{\partial \frac{ki}{n}}{\partial z} \qquad (39)$$

h_w = heat flux in the water alone

h_{sw} = heat flux from soil to water

The heat flux from the soil to the water must be the negative of the heat flux from soil to water or

$$h_{sw} + h_{ws} = 0 \qquad (40)$$

where

α_w = coefficient of heat conductivity of the water and

The specific heat concept can be applied to the soil and water to give

$$\frac{\partial\ h_s}{\partial\ z} = \frac{\gamma_s}{g}\ C_{vs}\ \frac{\partial\Theta_s}{\partial\ t} \tag{45}$$

where

$\gamma_s = G_s\gamma_o$ and

C_{vs}= specific heat of the soil

For the water the equation becomes

$$\frac{-\partial h_w}{\partial\ z} = \frac{\gamma_w}{g}\ C_{vw}\ \frac{\partial\ \Theta_w}{\partial\ t} \tag{46}$$

where

$\gamma_w = G_w\gamma_o$ and

C_{vw} = the specific heat of the water

When the two equations for either the soil or water are combined, the classic heat equation results.

$$\frac{\partial^2\Theta}{\partial z^2} = \left[\frac{C_v\gamma_\alpha}{g}\right]\frac{\partial\ \Theta}{\partial\ t} \tag{47}$$

For the soil the term in the brackets is a function of porosity, n, and must be evaluated experimentally.

For the water the steady state condition is, $\frac{\partial\Theta}{\partial t} = 0$, therefore:

$$\frac{\partial^2\Theta}{\partial z^2} = 0, \tag{48}$$

$$\frac{\partial\Theta}{\partial z} = \text{a constant} = F, \text{ and} \tag{49}$$

Θ = G+Jz where G and J are arbitrary constants. This last equation is borne out by temperature measurements in oil wells, and lends credence to the general theory.

III. Derivation of the Geostatic Pore Pressure Equation

Before the mechanics of pore pressures can be developed further, it is necessary to consider the effect of temperature and pressure on the density of sea water.

The non-linear specific gravity of sea water has been developed from data in the literature (34), with salinities between 30% and 40%, and it was found that:

$$G_w = g(\Theta) + f(u) + uh(\Theta) \tag{50}$$

where:

$$g(\Theta) = 1.02753169 + 6.36 \times 10^{-6}\,\Theta - 6.52 \times 10^{-6}\,\Theta^2 + 2.0 \times 10^{-8}\,\Theta^3 \tag{51}$$

$$f(u) = 2.992 \times 10^{-5}\,u \tag{52}$$

$$h(\Theta) = 1.6 \times 10^{-7}\,\Theta - 1.0 \times 10^{-8}\,\Theta^2 \tag{53}$$

u is the water pressure in psi (0-10,000 psi, range) and Θ is the temperature in ° centrigrade (0-200°C, range) where the percent error is never greater than 0.17%.

When the linear sub-bottom profile temperature equation,

$$\Theta = G + Jz \tag{54}$$

is combined with the specific gravity equation, them the following equation results.

$$G_w = g_1(z) + f(u) + u\,h_1(z). \tag{55}$$

It will be seen that for the hydrostatic case with mo excess pore pressure or upward flow equilibrium requires that

$$\frac{\partial u}{\partial z} = G_w \gamma_o = g_1(z) + f(u) + uh_1(z) \tag{56}$$

where g_1, and h_1 are new functions of depth.

This nonlinear equation has a unique solution (Riccati form). It determines the hydrostatic pressure as a non-linear function of depth. The solution of this non-linear equation is given in Appendix I.

The specific gravity equation is particularly useful in all the field equations where the water usually has been taken as incompressible.

IV. Shear Deformation During Progressive Burial

The ratio of the principal effective stresses is called K. In the one-dimensional or uniaxial strain process, like progressive burial, the principal stresses are horizontal and vertical and K is called K_o. At the mudline, $K_o = 1$ because the soil has little or no cohesive strength. It is being found that as the material is progressively buried to greater depths, the porosity decreases and cohesive strength A develops causing K_o to decrease. There is a limit to this process and, when $K = K_f$, the material fails in shear, fractures develop, and friction becomes the dominating strength property. At this point, permeability radically increases since water can flow through the discontinuities. It is believed that this is the effect being seen when the Mississippi delta sediment reached 13% porosity.

Probably further burial causes the cracks to close; and the permeability decreases as the porosity decreases. This event probably occurs at large pressures unless upheaval has occurred to lower the hydrostatic pressure.

These points are illustrated mathematically in the following way. In the uniaxial test the mean principal stress, σ_m, can be shown to be:

$$\sigma_m = \sigma_v \frac{(1+2K_o)}{3} \tag{57}$$

where: σ_v is the vertical stress, and

K_o is the coefficient of earth stress at rest.

Also, in the uniaxial test the octahedral shear stress, τ_{oct}, can be shown to be:

$$\tau_{oct} = \frac{\sqrt{2}}{3} (1-K_o)\, \sigma_v \tag{58}$$

Experimental results, extrapolated for the Weld clays, show that:

$$\sigma_{mo} = D_n^{R} \tag{59}$$

$$\sigma_{mf} = Bn^R \tag{60}$$

$$\tau_{octf} = Cn^R \tag{61}$$

where: D, B, C and R are constants for the materials,

σ_{mo} is the mean principal stress when there are no shear stresses,

σ_{mf} is the mean principal stress at shear failure,

τ_{octf} is the octahedral shear stress at failure, and

n is the porosity.

Since K_o must vary between one and zero as porosity n varies between 100% and zero, a one to one correspondance might be assumed. If K_o is equal to n then the τ_{octf} can be related to σ_{mf} by the following equations:

$$\frac{C}{B} = \frac{\tau_{octf}}{\sigma_{mf}} = \frac{\sigma_v \frac{\sqrt{2}}{3} (1-K_o)}{\sigma_v \left(\frac{1+2K_o}{3}\right)} \tag{62}$$

to give the porosity:

$$n = \frac{\sqrt{2}B-C}{2C + \sqrt{2}B} \quad \text{at shear failure,} \tag{63}$$

the vertical stress:

$$\sigma_v = \frac{3Dn^R}{(\frac{D-B}{C})\ (\sqrt{2}(1-K_o)) + (1+2K_o)} \tag{64}$$

in the range of porosities before failure, and

$$\sigma_v = \frac{3Dn^R}{1+2n} \text{ after failure.}$$

These relationships are shown in Figure 3.

V. Further Developments and Boundary Conditions

There have been other developments in the study of the transient flow of water through soil as the hydraulic gradient is changed. The application of gas partial pressure concepts to the problem has been considered. All of the equations have been combined with the equations for the stress-porosity, and permeability-porosity developed in the experimental part of the work, however, this work is not yet finished.

Before the equations can be integrated, boundary or initial conditions must be developed for all variables to be studied. The physical boundaries are the bottom of ocean Z_b, the ocean surface Z_s and the elevation of the sedimentary basement Z_r. The initial time t_o can be set at any value.

At the ocean bottom the porosity n is usually around 78% to 80% depending on the type of mineral. The temperature Θ is always above freezing and approximately 2°C at abyssal depths. Near shore, the bottom temperature approaches the average ground temperature and in temperate zones near 20°C. The pore pressure u is equal to the weight of the water over the bottom. The variation of pore pressure u versus depth for oceans is pretty well known. These values would hold for all times.

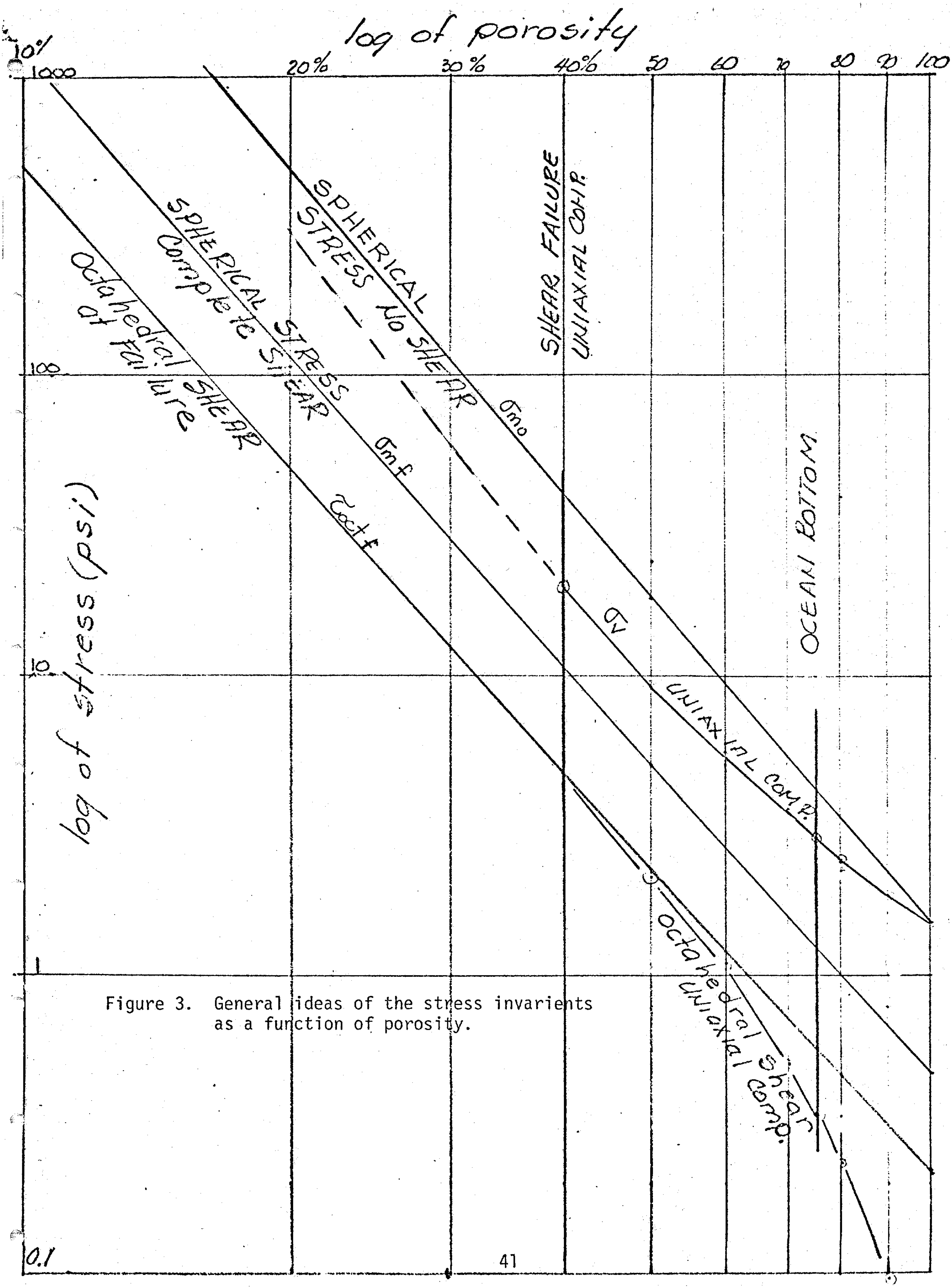


Figure 3. General ideas of the stress invarients as a function of porosity.

The rate of soil deposition on the bottom in mass per unit area per unit time and the rate of rise or fall of the ocean surface are the last two boundary conditions required. The first may be estimated from suspended sediment analysis; the last will have to come from geologic studies.

EXPERIMENTAL STUDY

Test Equipment and Procedure

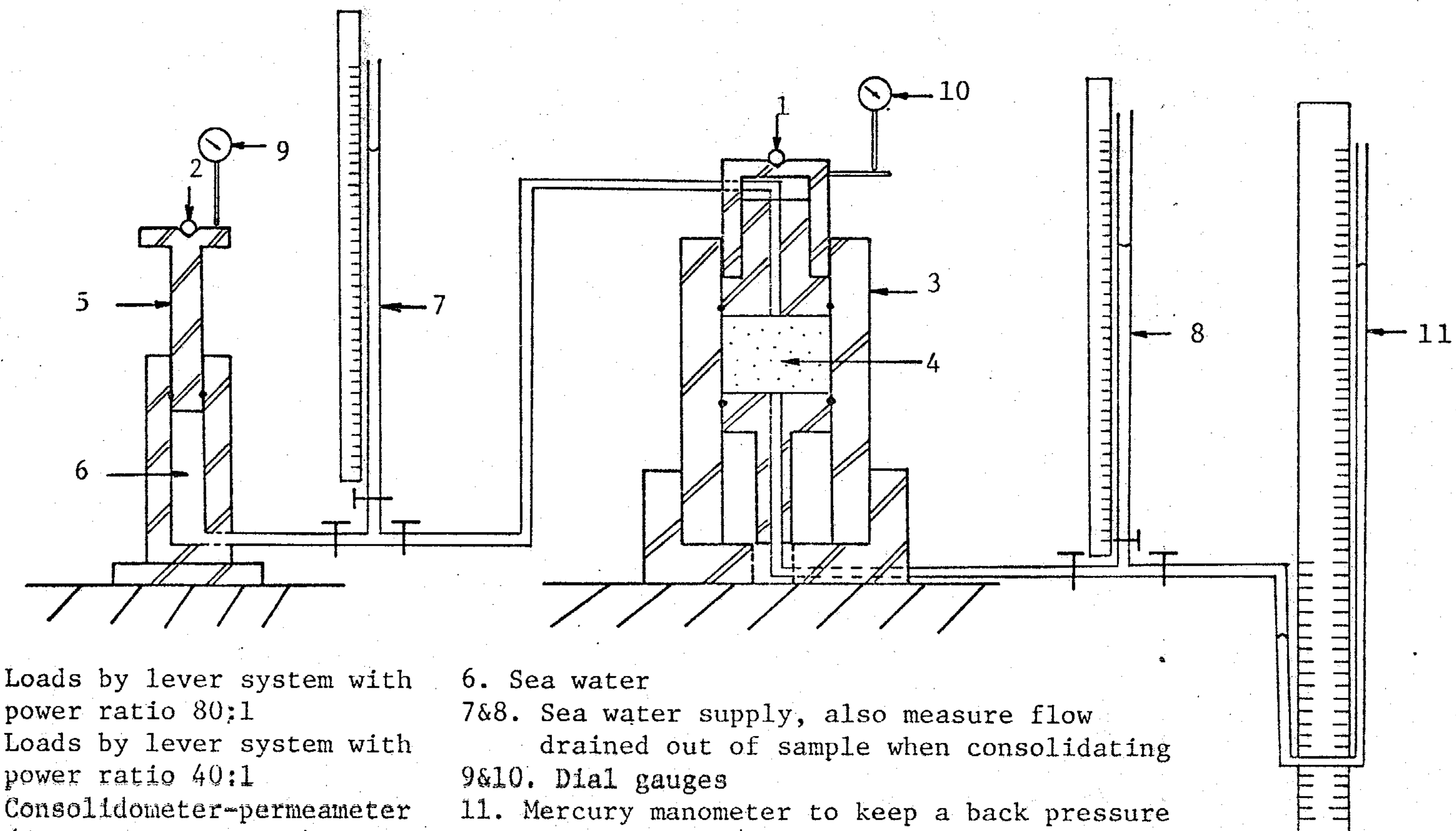
A consolidometer-permeameter was built to test soil sample to pressures of 10,000 psi. All the consolidation loads were measured directly using dead weights and lever systems. There were no electronics, transducers, load cells, strain gauges, proving rings or other devices that need calibration or study to prevent misunderstanding of the data being obtained. All flow rates were measured in graduates at atmospheric pressure and room temperature. The soil samples used were 2.5" in diameter and 1.5" to 2" long. Starting with a submarine saturated slurry, a load was applied by the lever system and sea water was pressed out of the sample. The load was left on long enough for the porosity to become constant. Sea water was then forced through the sample by another lever system until the flow rate reached a constant. This process was repeated by increasing the load on the main lever system until 10,000 psi was reached. Schematic drawing of the equipment are shown in Figures 4 and 5.

Soil Samples

The soil samples for this study were taken from sea bottom at three different locations. The locations of the core samples are described in Table 3.

The Atterberg limits, Unified Soil Classification, and specific gravity for each soil are given in Table 4.

The mineralogical analysis, determined by x-ray diffraction, of the three materials is given in Table 5.



1. Loads by lever system with power ratio 80:1
2. Loads by lever system with power ratio 40:1
3. Consolidometer-permeameter (detais in FIG. 5)
4. Soil sample
5. Piston to apply water pressure

6. Sea water

7&8. Sea water supply, also measure flow drained out of sample when consolidating

9&10. Dial gauges

11. Mercury manometer to keep a back pressure and measure flow through sample when testing permeability

FIG. 4.-Schematic Drawing of Testing Apparatus for High Pressured Consolidation Test and Direct Measurement of Permeability

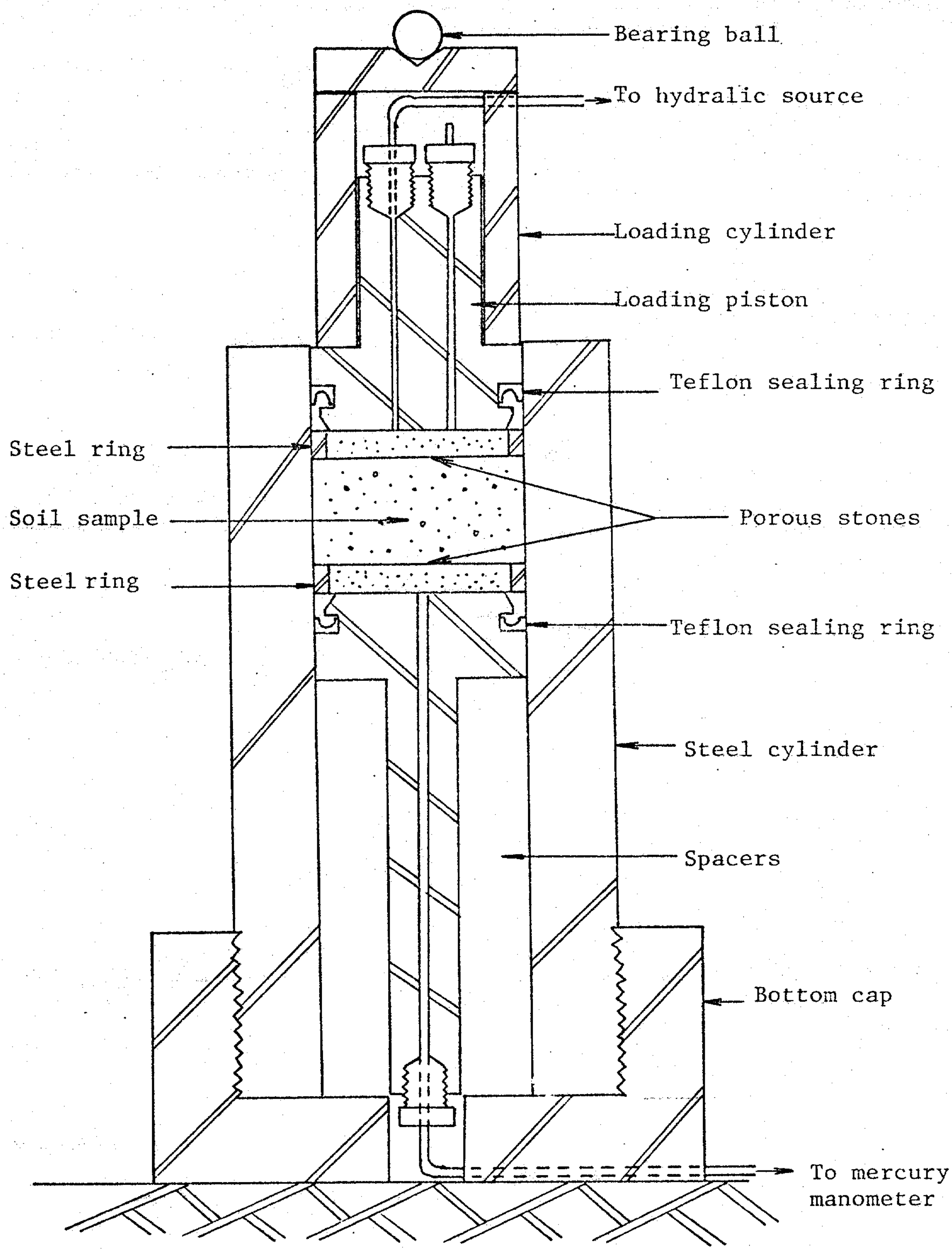


FIG. 5.-Schematic Drawing of the Consolidometer-Permeameter

TABLE 3. Locations of Three Soil Samples

Material	Location	Depth
Virginia Sediment	Lat. 36 59' N Long. 76 07' W Chesapeake Bay	Surface of sea bottom in very shallow water
Mississippi Delta Sediment	Lat. 29 28' N Long. 92 21' W Central Gulf of Mexico	20 meters below sea surface 0.5 meter below sea bottom
Gulf of Mexico Sediment	Lat. 26 58' N Long. 94 15' W Western Gulf of Mexico	2,379 meters below sea surface 1.5 meters below sea bottom

TABLE 4. Atterberg Limits, Classifications, and Specific Gravities of Three Soil Samples

Material	Liquid Limit	Plastic Limit	Plasticity Index	Classification	Specific Gravity
Virginia Sediment	59.3	39.3	20	MH	2.70
Mississippi Delta Sediment	113.2	32.8	80.4	CH	2.81
Gulf of Mexico Sediment	91.0	34.0	57.0	CH	2.77

TABLE 5. Mineralogical Analysis of Three Soil Samples

Minerals	Virginia Sediment	Mississippi Delta Sediment	Gulf of Mexico Sediment
Smectite		61.0	67.0
Illite	52.0	17.0	17.0
Kaolinite	36.0	17.0	12.0
Chlorite		5.0	4.0
Vermiculite	7.0		
Quartz	5.0		

Consolidation of Test Results

The plot of sample height versus log of time for each increment of load and for each soil is given in Appendix II. From the total change of sample height, the change in void ratio and change in porosity were computed. The e-log p curves of the three samples are shown in Fig. 6. The consolidation pressure for these tests ranged from 36 psi (248.2 KPa) to 10,125 psi (69.812 MPa). The test data are shown in Appendix II. The porosities were plotted on a log-log scale against consolidation pressures which showed the porosity as a function of vertical pressure in the process of progressive burial.

The Fermi function (30) was used as a mathematical model to fit the test data. It shows the model fits the curve very well within the range of test loads. The equation was developed as follows:

$$\log n = \frac{-1}{1 + e^{S \log \sigma + T}} \qquad (66)$$

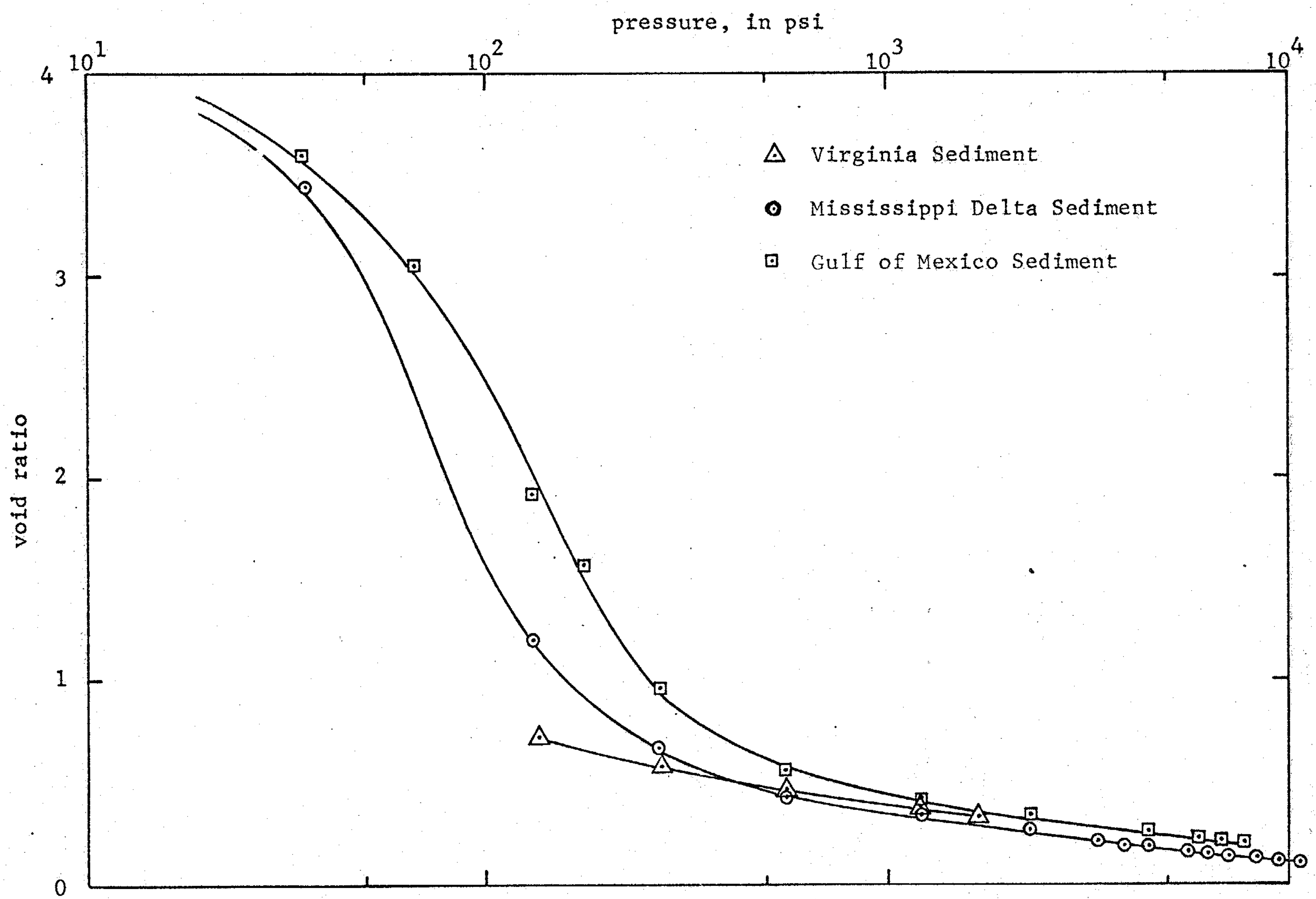


FIG. 6 .-Relationship between Void Ratio and Log of Pressure for Three Soil Samples

where σ = vertical consolidation stress, in psi,

n = decimal porosity

e = 2.71828

S = the slope of the function at the point of reflection

T/S = the distance from the point of reflection to Y axis in the rectangular co-ordinate system.

The Fermi functions derived for Virginia sediment, Mississippi Delta sediment and Gulf of Mexico sediment are shown in Figures 7, 8, and 9.

Permeability Test Results

The permeability tests were performed after each increment of consolidation test. The flow was plotted against time until a steady state of flow was achieved. It was assumed a steady state was developed when the flow stayed constant with increasing time. The plot of flow versus time, the calculation of permeability and the results of permeability tests are given in the Appendix II.

The permeabilities were plotted against porosities on a log-log scale. The power law model was used to fit the test data.

It was developed as follows:

$$k = Qn^M, \qquad M < 0 \text{ and } \qquad Q > 0 \tag{67}$$

where: k = coefficient of permeability

Q = the intercept of the line when the decimal porosity is one

M = the slope of the line

n = decimal porosity

Q and M are constants but peculiar for each type of soil.

The curves are shown in Figures 10, 11 and 12.

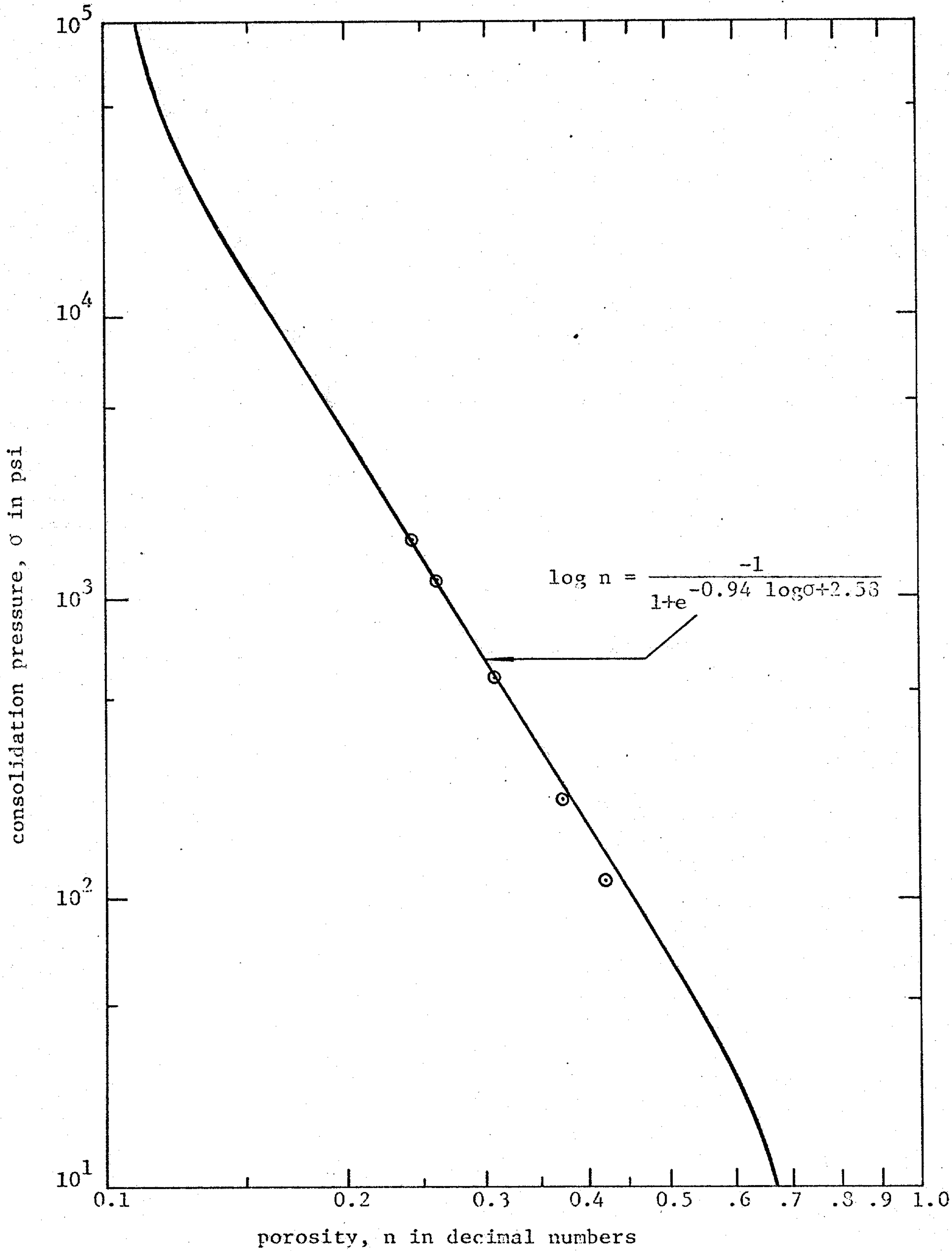


FIG. 7 .- Relationship Between Consolidation Pressure and Porosity for Virginia Sediment by the Fermi Function Model

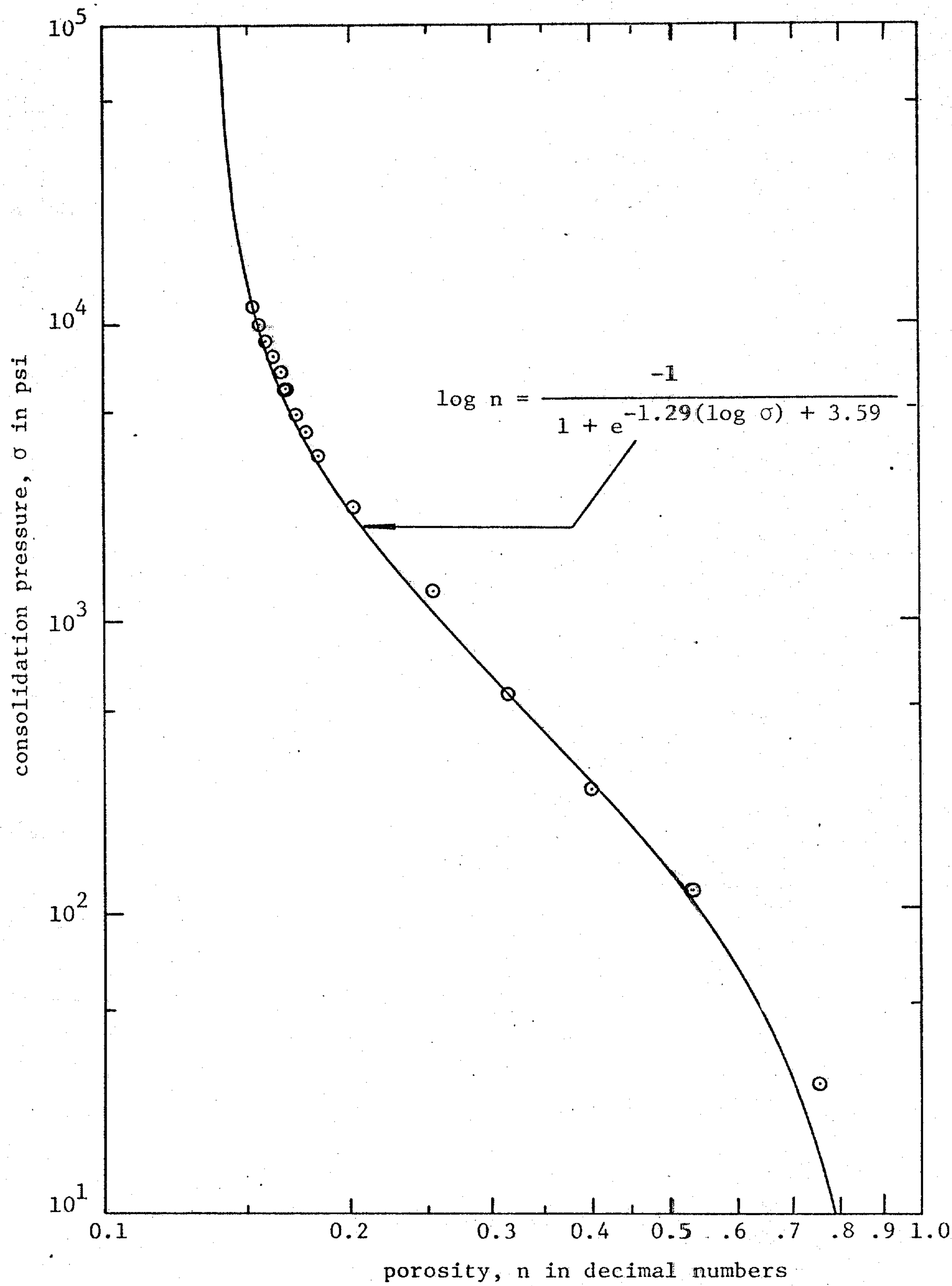


FIG. 8 .-Relationship Between Consolidation Pressure and Porosity for Mississippi Delta Sediment by Fermi Function Model

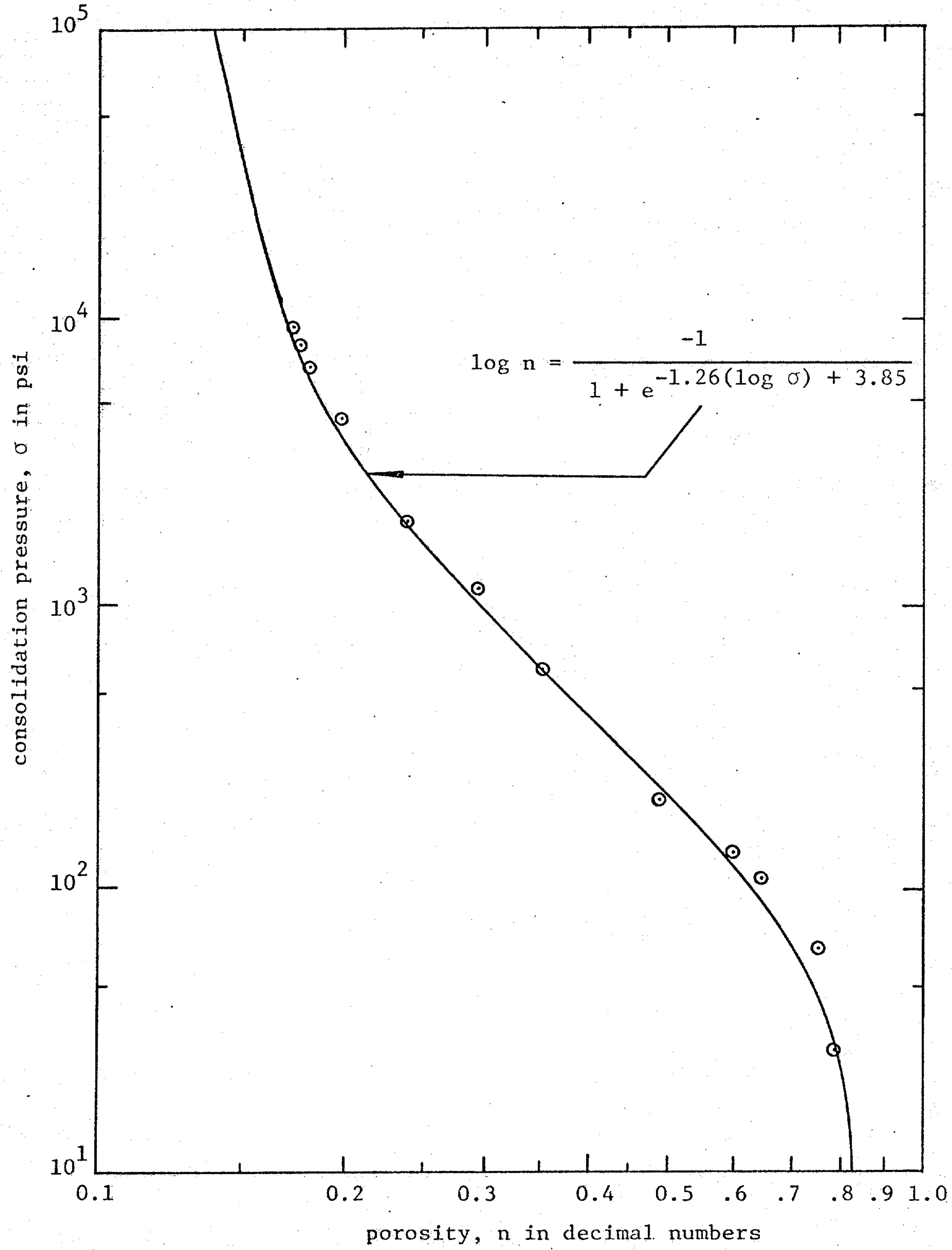


FIG. 9.-Relationship Between Consolidation Pressure and Porosity for Gulf of Mexico Sediment by Fermi Function Model

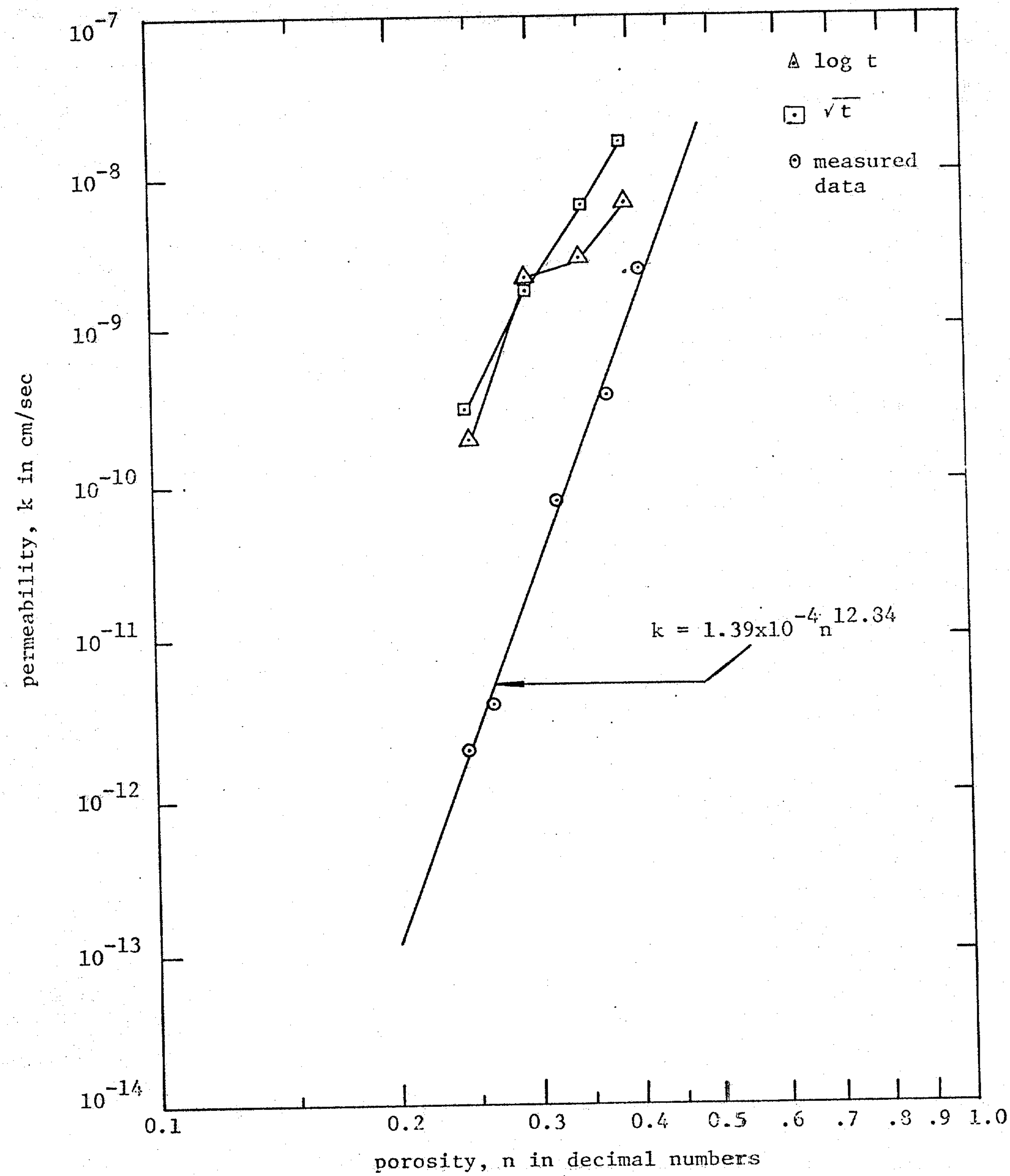


FIG. 10.- Relationship Between Permeability and Porosity for Virginia Sediment by Power Law Model

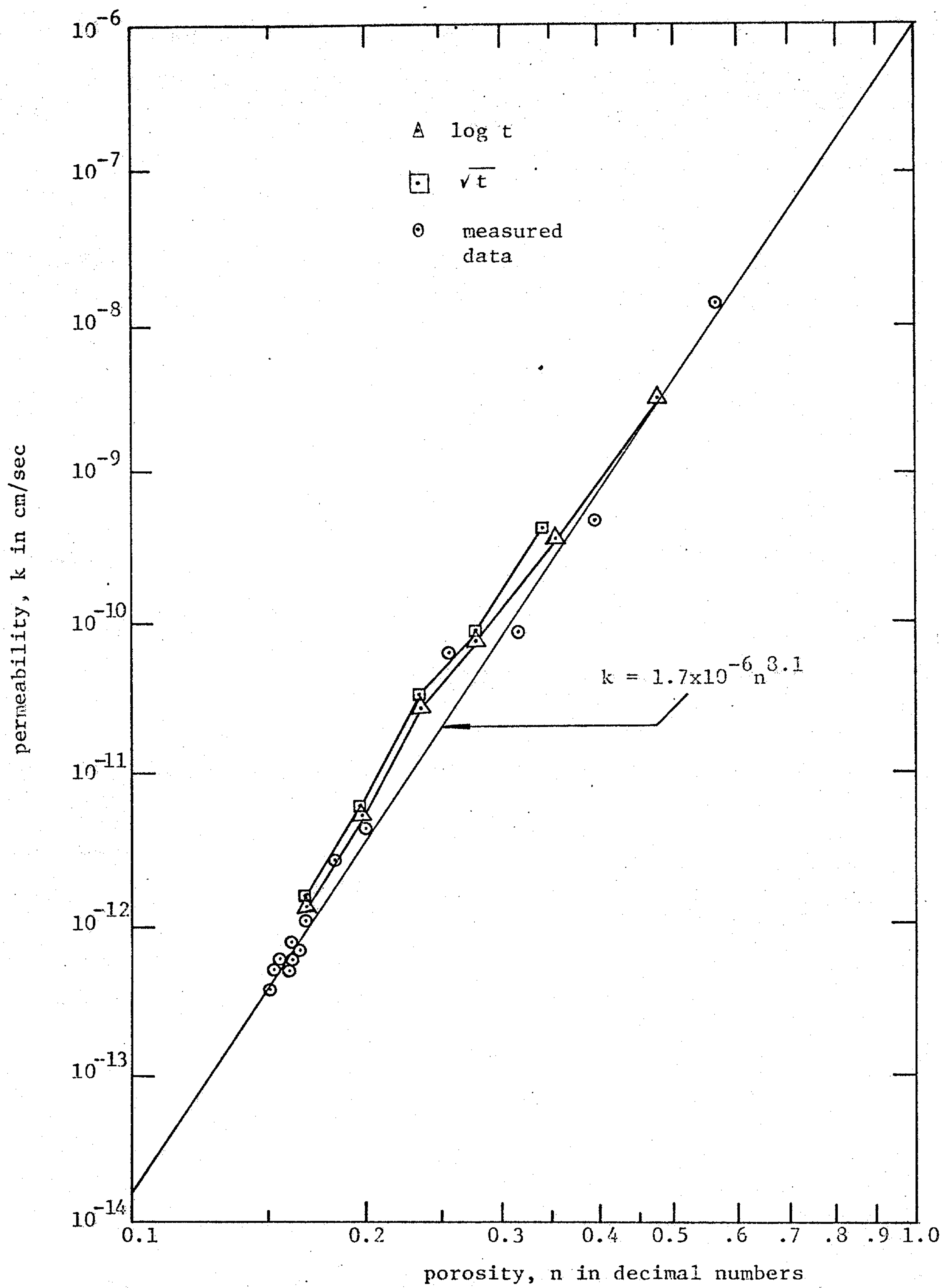


FIG. 11 .- Relationship Between Permeability and Porosity for Mississippi Delta Sediment by Power Law Model

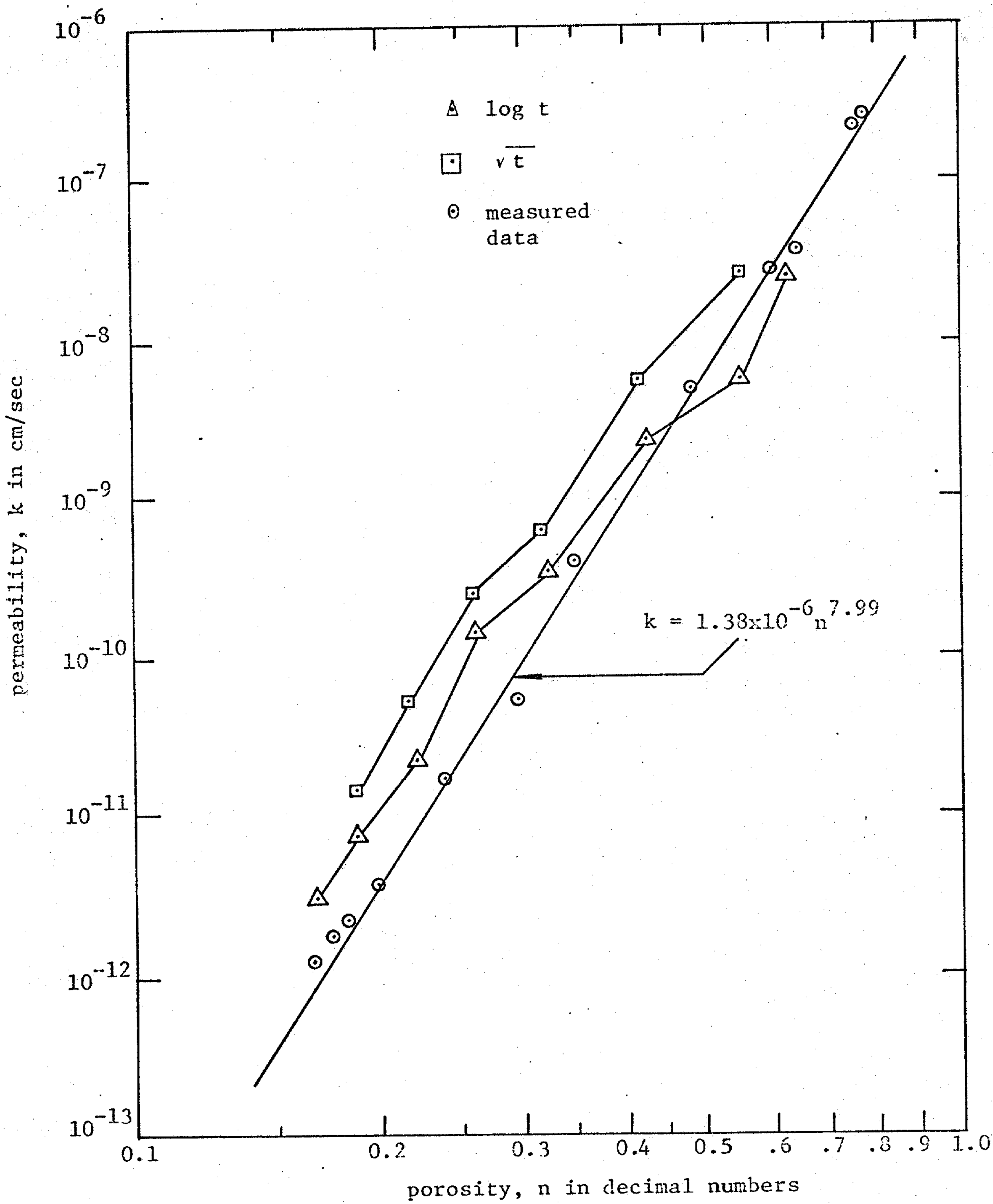


FIG. 12.- Relationship Between Permeability and Porosity for Gulf of Mexico Sediment by Power Law Model

The consolidation test data were used to calculate the coefficient of permeability by Terzaghi's theory (67). Two methods were used to obtain the coefficient of consolidation. The $\sqrt{t}$ fitting method appeared to have a higher value of the coefficient of permeability than the log t fitting method. However, both values are slightly higher than the tested values by zero to one order of magnitude. The results were plotted in Figures 10, 11, and 12.

The rate of change of permeability with respect to porosity can be computed from the permeability equation:

$$\frac{dk}{dn} = QMn^{M-1} \tag{68}$$

This rate of change is a function of porosity and is plotted on the permeability figures for the Mississippi delta sediment and Gulf of Mexico sediment. This is shown in Figures 13 and 14.

Conclusions for Experimental Part of the Study

A new experimental method of obtaining high pressure consolidation test data and direct measurement of permeability has been developed. Based on the results obtained it is concluded that:

1. The marine sediments tested did not exhibit the usually assumed linear relationship between void ratio and log of consolidation pressure.
2. There is maximum porosity for each marine sediment.
3. Permeabilities of clays can be measured directly and there is no need to estimate this value using the Terzaghi's consolidation theory. In fact, there can be wide discrepancies between the measured permeability and that permeability computed from a consolidation test.

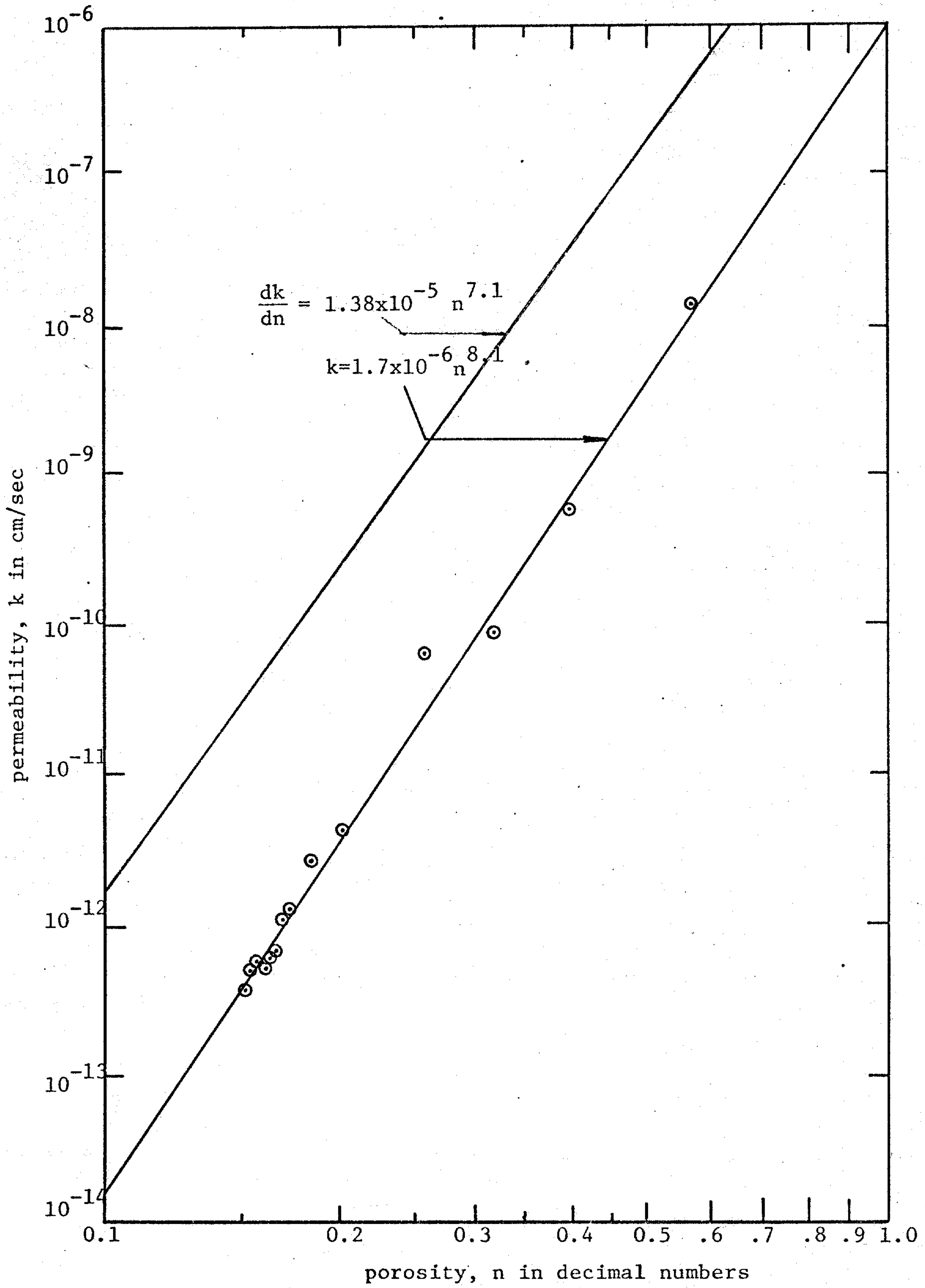


FIG. 13.-Relationship Between Permeability and Porosity for Mississippi Delta Sediment by Power Law Model and the Relationship for Rate of Change of Permeability with Respect to Porosity.

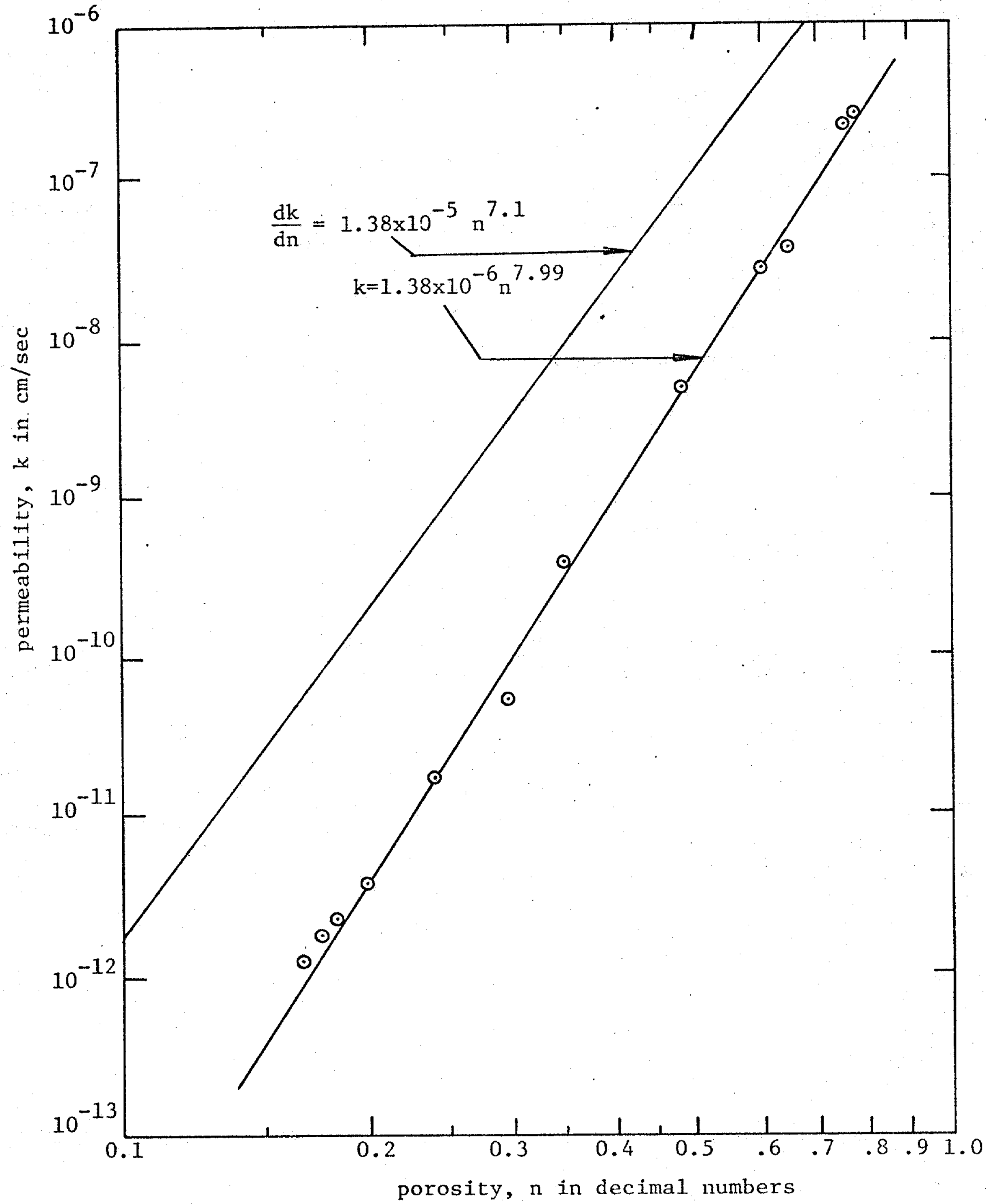


FIG. 14.-Relationship Between Permeability and Porosity for Gulf of Mexico Sediment by Power Law Model and the relationship for rate of change of permeability with respect to porosity.

4. The Fermi function seems to be a good model for the relationship between the porosity and the consolidation pressure.
5. The power law seems to be an excellent model for the relationship between porosity and permeability.
6. The permeability decreased at least seven orders of magnitude faster than the porosity for the materials tested.

Further work should be done to include a controlled thermal environment as a method to investigate the temperature effect on the relationship between pressure, permeability, and porosity. More soil samples should be tested to provide a general correlation among the same type of soil.

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Appendix I

Solution of the Non-Linear Differential Equation for the Geostatic Pore Pressure When the Temperature Varies Linearly with Depth.

The pore-pressure u considered here is only geostatic pressure and includes no overpressure or excess pressure, z is the depth and θ is the temperature. The equation is derived and terms define in part III of the Theoretical Part of the Study.

As given:

$$\frac{du}{dz} = g_1(z) + f\,(u) + uh_1(z) \tag{56}$$

where,

$$\left.\begin{aligned} g_1(z) &= A_1 z + A_2 z^2 + A_3 z^3 \\ f\,(u) &= B_1 u + B_2 u^2 \\ &\text{and} \\ h_1(z) &= C_1 z + C_2 z^2. \end{aligned}\right\} \quad \text{as defined by equations (51) through (54)}$$

A recombination of terms gives:

$$\frac{du}{dz} - (B_1 + C_1 z + C_2 z^2)u - B_2 u^2 = 1 + A_1 z + A_2 z^2 + A_3 z^3 \tag{69}$$

or,

$$\frac{du}{dz} - g_2(z)u - B_2 u^2 = f(z) \tag{70}$$

where $g_2(z) = B_1 + C_1 z + C_2 z^2$ (71)

and $f_1(z) = 1 + A_1 z + A_2 z^2 + A_3 z^3$. (72)

For the first transformation let $u = \frac{y(z)}{B_2}$, then, $u' = \frac{y'(z)}{B_2}$. (73), (74)

Substitution into the equation gives

$$\frac{y'(z)}{B_2} - g(z)\,\frac{y(z)}{B_2} - \frac{B_2(y(z))^2}{(B_2)^2} = f(z) \tag{75}$$

and when terms are cancelled

$$y' - g(z)\,y' - y^2 = B_2 f(z)\,. \tag{76}$$

For the second transformation let

$$y = w - \frac{g(z)}{2} \tag{77}$$

$$\text{then } y^2 = w^2 - g(z)w + \frac{g^2(z)}{4} \tag{78}$$

$$\text{and } y' = w' - \frac{g'(z)}{2}\,. \tag{79}$$

Substitution into the equation gives

$$w' - \frac{g'(z)}{2} - g(z)\left[w - \frac{g(z)}{2}\right] - w^2 + g(z)\,w \tag{80}$$

$$- \frac{g^2(z)}{4} = B_2\ f(z) \tag{81}$$

or with cancellation of terms.

$$w' - w^2 = \frac{g'(z)}{2} - \frac{g^2(z)}{4} + B_2 f(z). \tag{82}$$

The function of z on the left side of the equal sign can be called

$$h(z) = \frac{g'(z)}{2} - \frac{g^2(z)}{4} + B_2 f(z) \tag{83}$$

$$\text{then } w' - w^2 = h\ (z) \tag{84}$$

For the third transformation let

$$w = - \frac{v'}{v} \tag{85}$$

$$\text{or } v = e^{-\int w dx} \tag{86}$$

$$\text{and } v' = - we^{-\int w dx}. \tag{87}$$

This means that

$$v' = -wv \tag{88}$$

$$\text{and } v'' = - wv' - vw' \tag{89}$$

$$\text{or } v'' = w^2 v - vw' = v(w^2 - w\ ). \tag{90}$$

$$\text{Since } w' = h(z) + w^2 \tag{91}$$

$$\text{then } v'' = v[w^2 - h(z) - w^2] \tag{92}$$

$$\text{or } v'' = -vh(z) \tag{93}$$

and finally

$$v'' + vh(z) = 0 \tag{94}$$

The nonlinear first order equation has now been transformed into a second order linear equaiton. The solution can be obtained by the method of undetermined coefficients.

$$\text{Let } v = A_0 + A_1 z + A_2 z^2 + \ldots\ldots. \tag{95}$$

and $v' = A_1 + 2A_2z + 3A_3z^2 + \ldots\ldots\ldots\ldots$ (96)

so that $v'' = 2A_2 + 6A_3z + 12A_4z^2 + \ldots\ldots\ldots\ldots$ (97)

where $h(z) = H_0 + H_1z + H_2z^2 + H_3z^3 + H_4z^4$ (98)

and the coefficients H_0 ---- H_4 are all known

Substitution into the equation gives

$2A_2 + 6A_3z + 12A_4z^2 + \ldots\ldots\ldots\ldots$ (99)

$+ (A_0 + A_1z + A_2z^2 + \ldots.)\ (H_0 + H_1z + H_2z^2 + H_3z^3 + H_4z^4) = 0$ (100)

Therefore the coefficients of the sum of the terms of the same power of z

$A_0H_0 + 0 + 2A_2 = 0$

$A_0H_1 + A_1H_0 + 0 + 6A_3 = 0$

$$\left.\begin{aligned} &A_0H_2 + A_1H_1 + A_2H_0 + 0 + 12A_4 = 0 \\ &A_0H_3 + A_1H_2 + A_2H_1 + A_3H_0 + 0 + 20A_5 = 0 \\ &A_0H_4 + A_1H_3 + A_2H_2 + A_3H_1 + A_4H_0 + 0 + 30A_6 = 0 \end{aligned}\right\} \quad (101)$$

$A_1H_4 + A_2H_3 + A_3H_2 + A_4H_1 + A_5H_0 + 0 + 42H_2 = 0$

Both A_0 and A_1 are known from boundary condition when $z = 0$.

The solution of this system of equations is as follows. The constants are polynomials of $(A_0, A_1, H_0, H_1, H_2, H_3 + H_4)$

$$\left.\begin{aligned} &A_2 = \frac{-A_0H_0}{2} \\ &A_3 = \frac{(A_0H_1 + A_1H_0)}{6} \\ &A_4 = \frac{(A_0H_2 + A_1H_1 + A_2H_0)}{12} = -\frac{(A_0(H_2 - \frac{H_0^2}{2} + A_1H_1)}{12} \end{aligned}\right\} \quad (102)$$

$$A_5 = \frac{(A_0H_3 + A_1H_2 + A_2H_1 + A_2H_0)}{20} = \frac{-(A_0(H_3 - \frac{H_0H_1}{2} - \frac{H_0H_1}{6}) + A_1(\frac{H_2 - H_0^2}{6}))}{20}$$

$$A_6 = \frac{(A_0H_4 + A_1H_3 + A_2H_1 + A_3H_1 + A_4H_0)}{30} =$$

$$A_7 = \frac{(A_1H_4 + A_2H_3 + A_3H_2 + A_4H_1 + A_5H_0)}{42} =$$

$$A_8 = \frac{(A_2H_4 + A_3H_3 + A_4H_2 + A_5H_1 + A_6H_0)}{56} = \qquad (102)$$

$$A_9 = \frac{(A_3H_4 + A_4H_3 + A_5H_2 + A_6H_1 + A_7H_0)}{63} =$$

$$A_{10} = \frac{-(A_4H_4 + A_5H_3 + A_6H_2 + A_7H_1 + A_8H_0)}{90} =$$

Substitution will show that A_1, A_2--- A_n are functions only of A_0, A_1 and the known coefficients H_0, H_1, H_2, H_3 and H_4 . The value of the A's are given by

$$A_2 = \frac{A_0H_0}{2}$$

$$A_3 = \frac{-(A_0H_1 + A_1H_0)}{6}$$

$$A_4 = \frac{-(A_0H_2 + A_1H_1 - A_0 \frac{H_0^2}{2}}{12} = \frac{-(A_0(H_2 - \frac{H_0^2}{2} + A_1H_1)}{12} \qquad (103)$$

$$A_5 = \frac{-(A_0H_3 + A_1H_2 - (\frac{A_0H_1H_0}{2} - \frac{A_0H_1H_0}{6} - \frac{A_1H_0^2}{6})}{12}$$

$$= \frac{-(A_0(H_3 - \frac{2}{3} H_1H_0) + A_1 (H - \frac{H_0^2}{6}))}{12}$$

$A_6 =$ .....

$\vdots$

Since the value of v is now known as function of z, using the inverse of the three transform will allow the geostatic pore pressure u to be calculated as a function of depth.

Appendix II

Experimental Study Calculation Methods and Test Data

CALCULATION OF PERMEABILITY

Darcy's equation is q = kia. The rate of flow, q, was calculated as described above after a steady state was reached. The pressure gradient, i, is the difference between head pressure and back pressure divided by the sample length. The cross sectional area of the soil sample is a, and the same as the area of the consolidometer.

For convenience, the conversion of units was reduced to a constant number:

$$q = kia \tag{104}$$

or

$$k = \frac{q}{ia} \tag{105}$$

$$q = \frac{(1/16)^2(\pi/4)(2.54)^2(\Delta h)}{(\Delta t)(60)} \text{ cm}^3/\text{sec} \tag{106}$$

$$i = \frac{(P-H/5.19)(70.43)}{(L)(2.54)} \text{ cm/cm} \tag{107}$$

$$a = (2.5)^2(\pi/4)(2.54)^2 = 31.67 \text{ cm}^2 \tag{108}$$

$$k = \frac{\dfrac{(1/16)^2(\pi/4)(2.54)^2(\Delta h)}{(\Delta t)(60)}}{\dfrac{(P-H/5.19)(70.43)}{(L)(2.54)}(31.67)} \tag{109}$$

after reduction:

$$k = 3.76\text{x}10^{-7} \frac{(\Delta h)(L)}{(P-H/5.19)(\Delta t)} \text{ cm/sec} \tag{110}$$

where Δh = change of water level at downstream end, cm.

L = length of sample, in.

P = head water pressure, psi.

H = mercury height (back pressure), cm.

Δt = elapsed time, min.

TABLE 6 .-Results of Consolidation and Permeability Test for Virginia Sediment

Load (psi)	Sample height (in.)	Void ratio, e	Porosity n (%)	Permeability k (cm/sec)
0	1.4248	2.533	71.7	-
143	0.6938	0.721	41.9	2.3×10^{-9}
286	0.6432	0.595	37.3	3.3×10^{-10}
572	0.5942	0.473	32.1	8.0×10^{-11}
1,144	0.5469	0.356	26.3	3.6×10^{-12}
1,716	0.5309	0.316	24.0	1.9×10^{-12}

TABLE 7.-Results of Consolidation and Permeability Test for Mississippi Delta Sediment

Load (psi)	Sample height (in.)	Void ratio, e	Porosity n (%)	Permeability k (cm/sec)
0	1.4459	3.710	78.77	-
36	1.3569	3.420	77.38	-
143	0.7128	1.220	54.93	$1.5x10^{-8}$
286	0.5061	0.650	39.34	$5.8x10^{-10}$
572	0.4467	0.460	31.28	$8.3x10^{-11}$
1,144	0.4129	0.350	25.65	$7.0x10^{-11}$
2,288	0.3855	0.260	20.37	$4.3x10^{-12}$
3,432	0.3747	0.220	18.07	$2.6x10^{-12}$
2,288	0.3755	0.223	18.25	-
4,004	0.3707	0.210	17.17	$1.2x10^{-12}$
4,576	0.3685	0.200	16.69	$1.1x10^{-12}$
5,720	0.3669	0.195	16.33	$4.9x10^{-13}$
6,570	0.3661	0.193	16.15	$5.5x10^{-13}$
7,714	0.3650	0.189	15.89	$4.0x10^{-13}$
8,500	0.3645	0.187	15.78	$4.5x10^{-13}$
9,313	0.3633	0.183	15.50	$4.0x10^{-13}$
10,125	0.3619	0.179	15.17	$3.8x10^{-13}$

TABLE 8.-Results of Consolidation and Permeability Test for Gulf of Mexico Sediment

Load (psi)	Sample height (in.)	Void ratio, e	Porosity n (%)	Permeability k (cm/sec)
0	2.1255	3.66	78.5	-
36	2.0716	3.54	78.0	2.8×10^{-7}
72	1.8327	3.01	75.1	2.4×10^{-7}
143	1.3131	1.88	65.2	4.0×10^{-8}
179	1.1568	1.53	60.5	3.1×10^{-8}
286	0.8852	0.94	48.5	1.2×10^{-9}
572	0.7026	0.54	35.1	3.0×10^{-10}
1,144	0.6467	0.42	29.4	6.4×10^{-11}
2,288	0.5991	0.31	23.8	1.3×10^{-11}
4,576	0.5701	0.25	19.9	3.2×10^{-12}
6,292	0.5541	0.215	17.7	1.9×10^{-12}
7,170	0.5529	0.212	17.5	1.6×10^{-12}
8,318	0.5509	0.208	17.2	1.2×10^{-12}

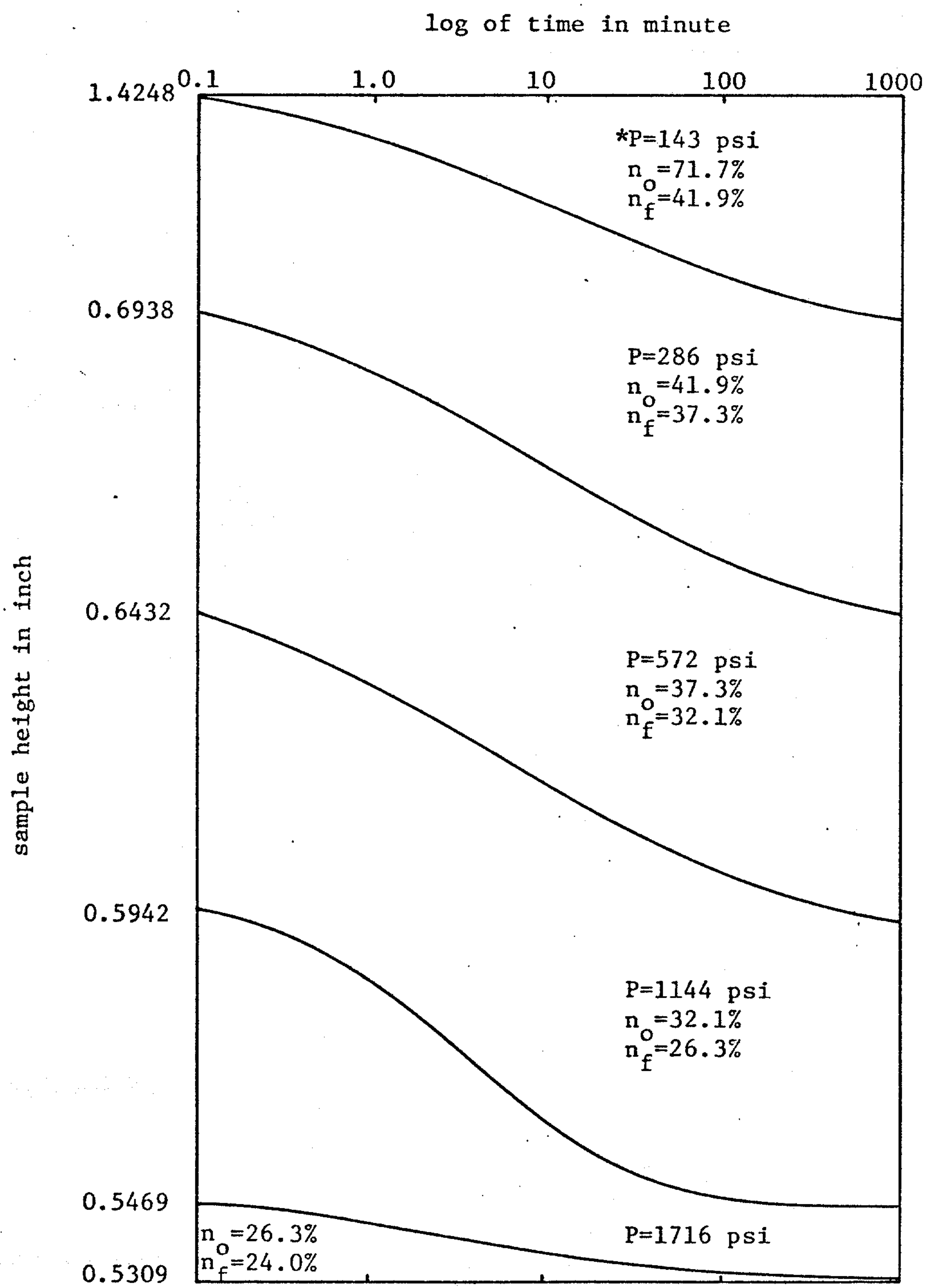

FIG. 15.-Relationship Between Sample Height and Log of Time of Consolidation Test for Virginia Sediment

*P=consolidation pressure
n_o=initial porosity
n_f=final porosity

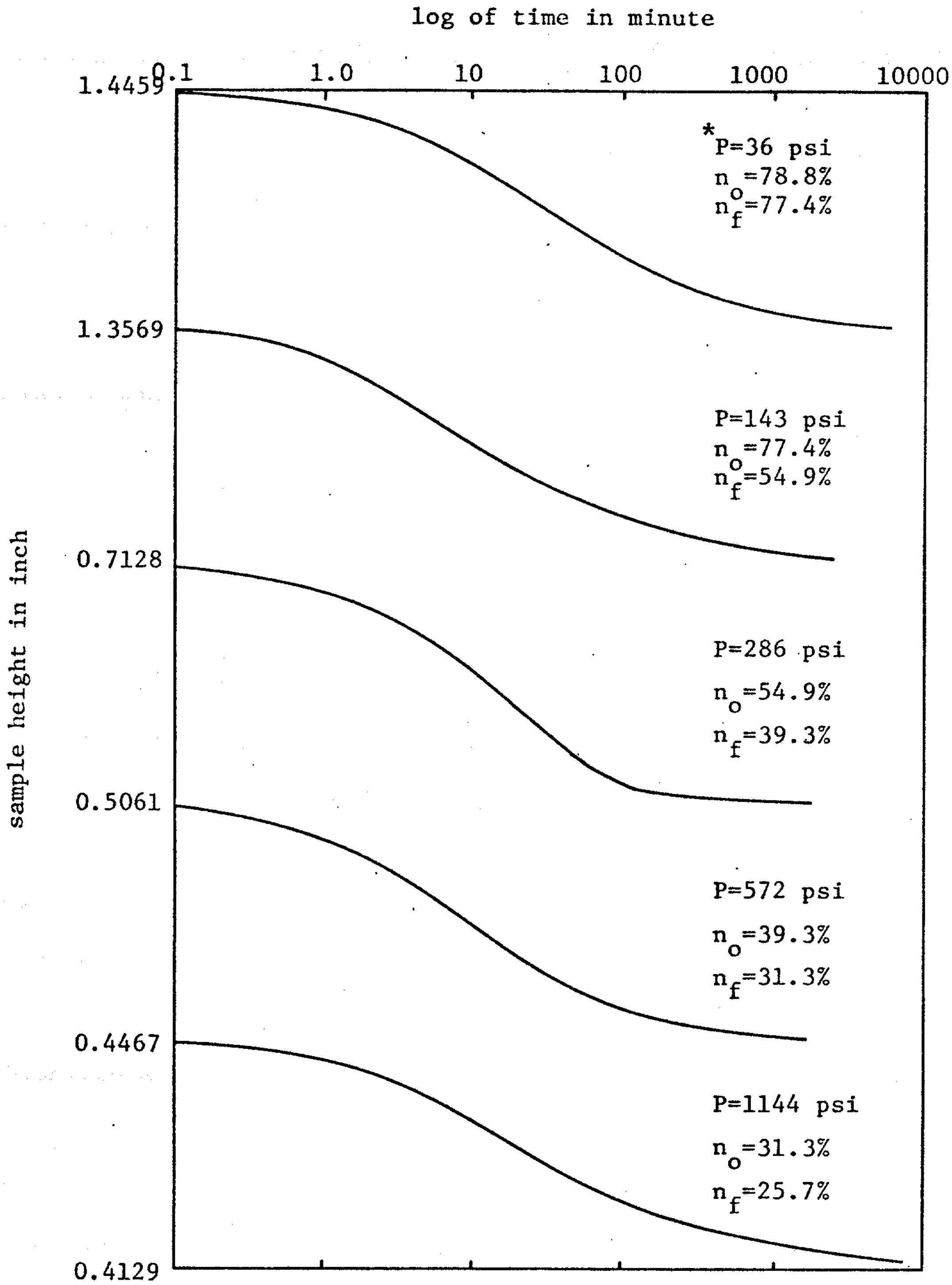

FIG. 16.-Relationship Between Sample Height and Log of Time of Consolidation Test for Mississippi Delta Sediment

*P=consolidation pressure
n_o=initial porosity
n_f=final porosity

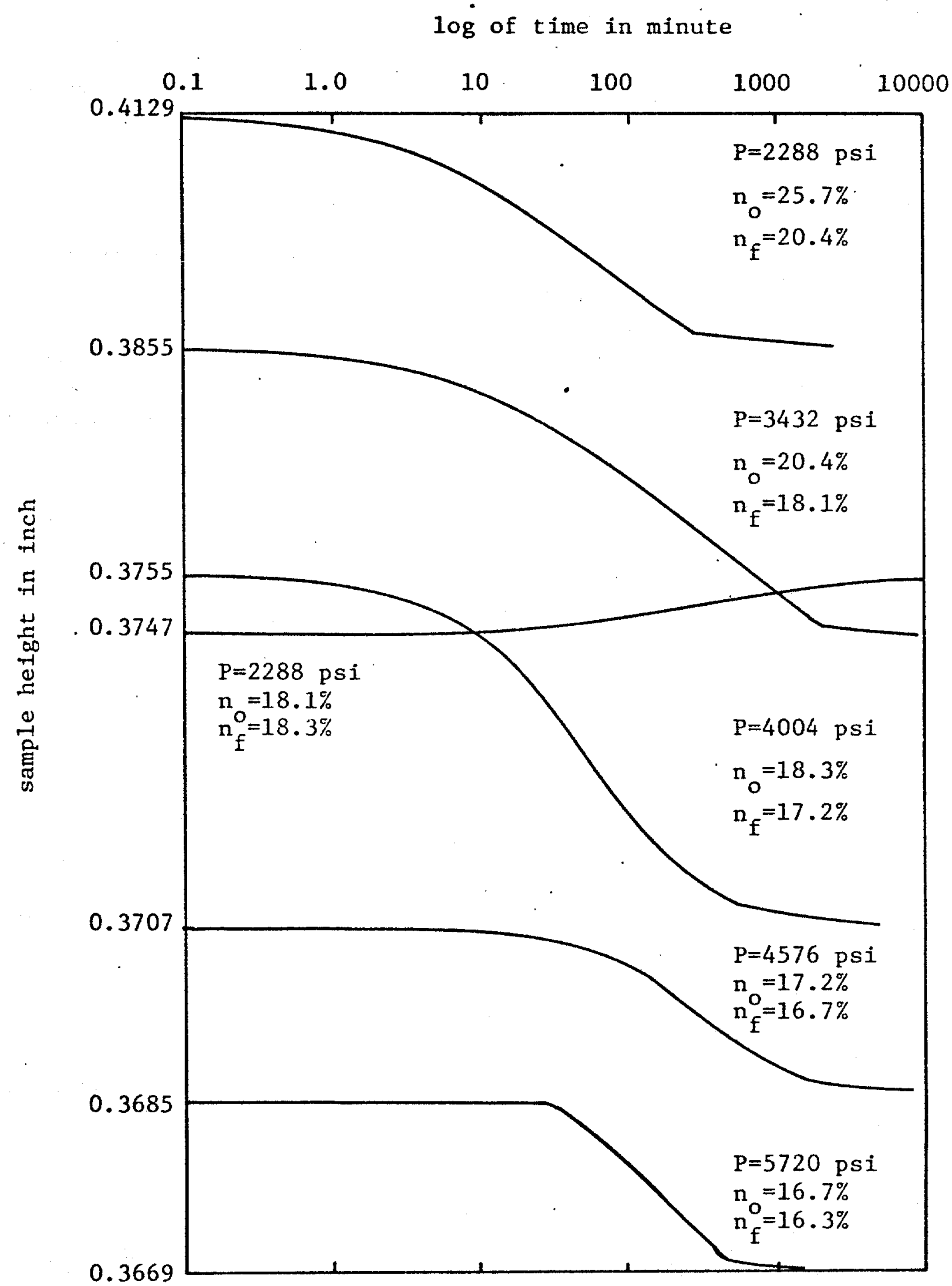

FIG. 16. (continued)

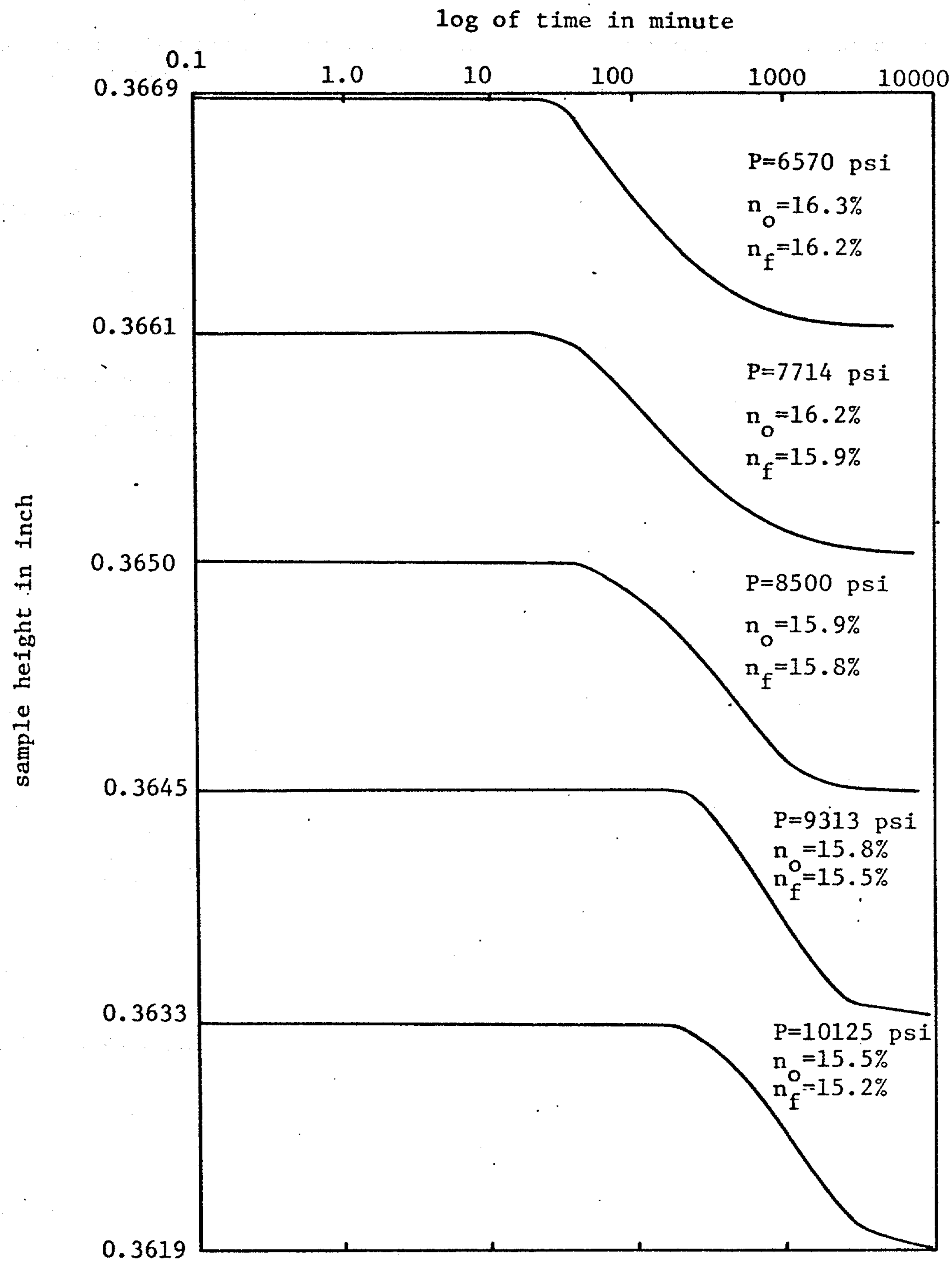

FIG. 16 . (continued)

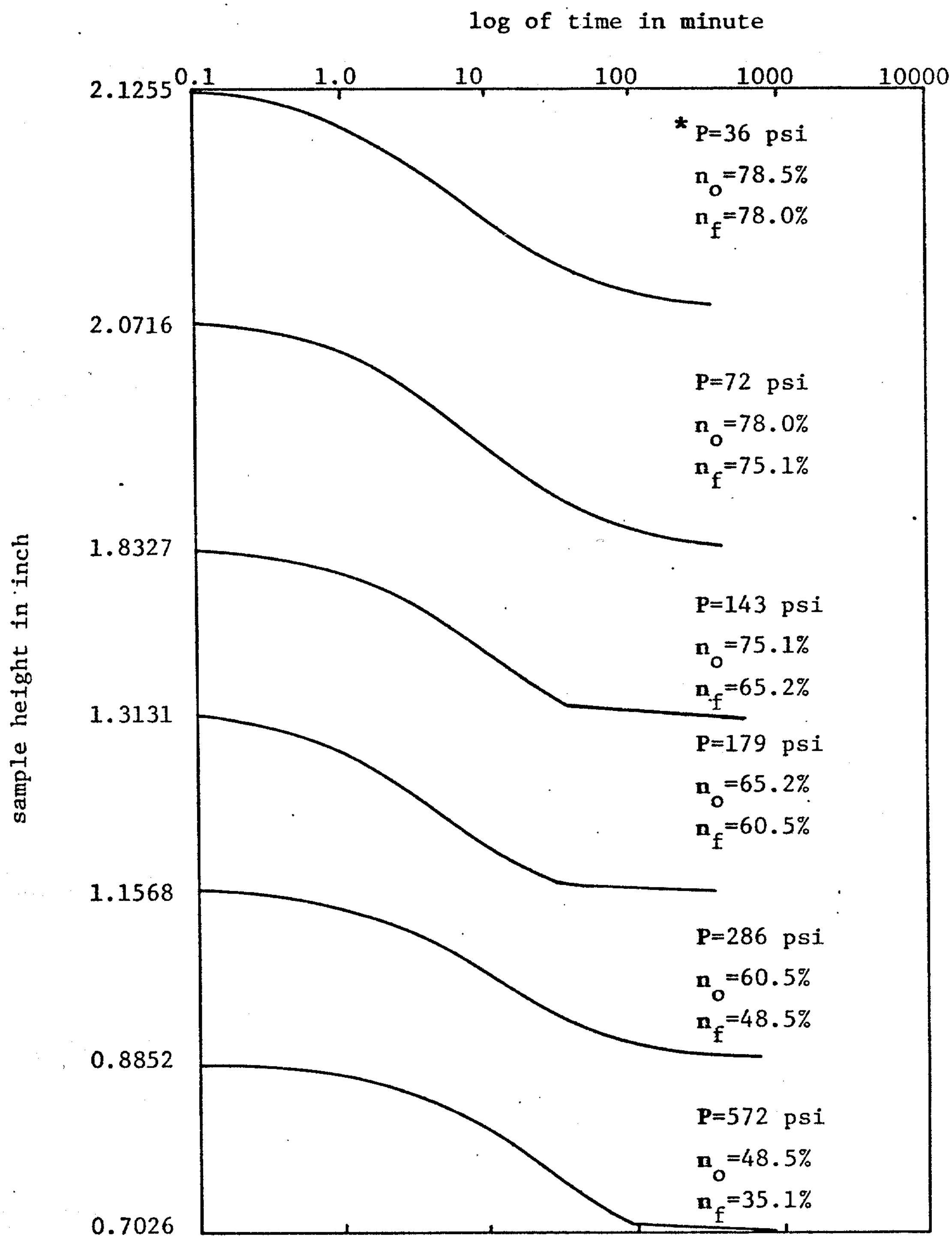

FIG. 17 -Relationship Between Sample Height and Log of Time of Consolidation Test for Gulf of Mexico Sediment

*P=consolidation pressure
n_o=initial porosity
n_f=final porosity

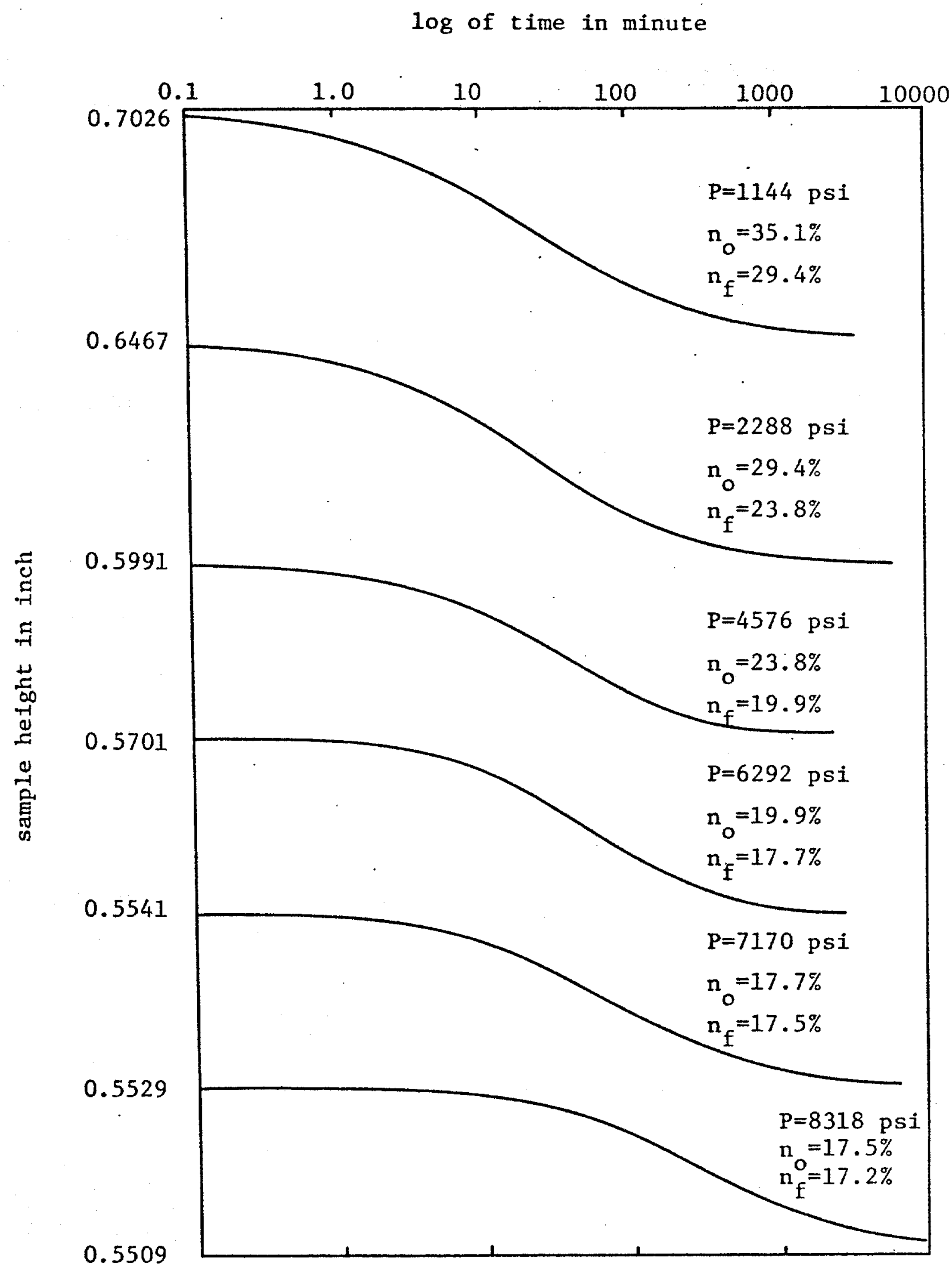

FIG. 17. (continued)

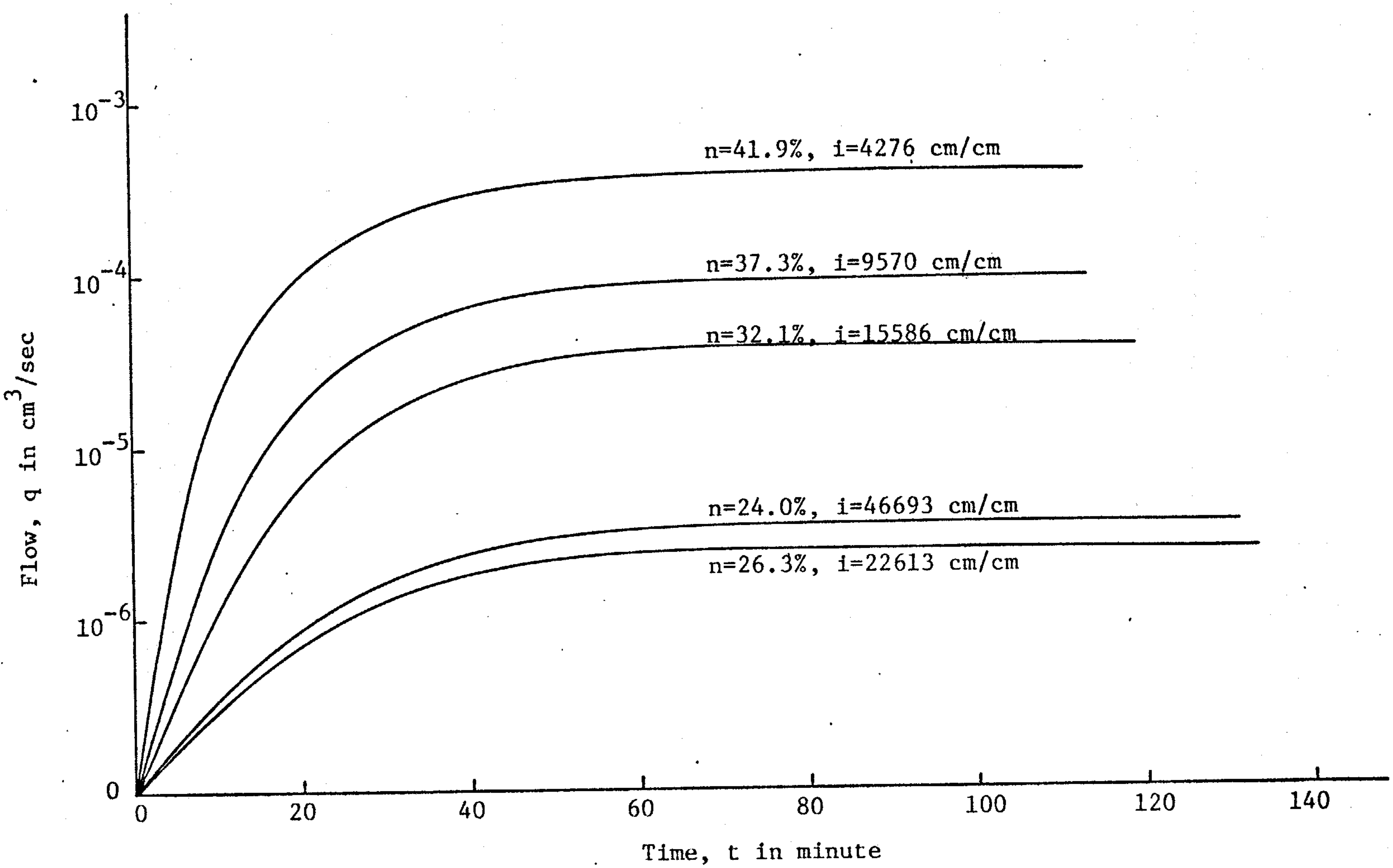

FIG. 18.-Relationship Between Flow and Time of Permeability Test for Virginia Sediment